The Environmental Kuznets Curve: Theory and Evidence

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List of Variables

- A Total factor productivity
- a Labour input requirement
- B Abatement
- b Abatement function in intensive form
- C Consumption
- c Chapter 3: unit production cost
  Chapter 4: consumption rate
- D Reunification dummy
- d Degree of homogeneity
- E Environmental effort (in Chapter 3 also a firm type)
- F Production function (in Chapter 3 also a firm type)
- f Function symbol
- G Gross pollution
- H Hamiltonian
- h Chapter 4: environmental effort rate
  Chapter 5: environmental effort-consumption ratio
- I Imports and exports relative to gross domestic product
- i Sector/good index
- j Index for general purpose technologies
- K Capital
- k Index for firm type
- L Labour (in Chapter 3 also a firm type)
- M Available resources (income)

- m Quality level index
- n Number of sectors with firms of a specific type
- P Pollution
- p Price of goods
- Q Harm from emission
- q Quality of goods
- R Specific firm type
- r Interest rate
- S Industry share of gross domestic product
- s Expected value of capital loss
- T Tax revenues (in Chapter 3 also a firm type)
- t Time index
- U Utility (in Chapter 3 also a firm type)
- V Vector of pollution affecting variables
- v Value of a firm
- w Wage
- X Total production
- x Production of a good
- Y Final output (Chapter 3: total consumption expenditures)
- y Spending per wage income
- Z Total emissions
- z Parameter reflecting the desire for a clean environment

- α Production elasticity of C in abatement
- β Production elasticity of E in abatement (private effect)
- γ Labour input requirement of GPT 3 (Chapter 3)
- Δ First difference of a variable
- δ Capital depreciation rate
- ε Normally distributed error term
- η Labour input requirement of GPT 2 (Chapter 3)

- Θ Extent of tax implementation
- θ Cost share (of pollution and labour, respectively)
- ι Research intensity
- Λ Pollution intensity parameter
- λ Chapter 3: quality difference
  Chapter 4: shadow price of capital
- π Profit
- ρ Time preference rate
- σ Estimation coefficient
- τ Tax rate
- υ Parameter reflecting the external effect of E on abatement
- ϕ Parameter reflecting the internal effect of C on gross pollution
- φ Estimation coefficient
- ψ Estimation coefficient
- ω Parameter reflecting the external effect of C on gross pollution

- $\mathcal{H}$ Hessian matrix

List of Abbreviations

CH_4	Methane
CL	Cost leader
CO	Carbon monoxide
CO_2	Carbon dioxide
CRS	Constant returns to scale
DEFRA	Department for Environment, Food and Rural Affairs (UK)
DESTATIS	Federal Statistical Office (Germany)
DW	Durbin-Watson
ECM	Error correction model
ECT	Error correction term
EKC	Environmental Kuznets curve
EPA	Environmental Protection Agency (USA)
GDP	Gross domestic product
Gg	Giga gramme
GGDC	Groningen Growth and Development Centre
GLS	Generalised least squares
GPT	General purpose technology
GSP	Gross state product
IRS	Increasing returns to scale
ITP	Income turning point
Kg	Kilogramme
LHS	Left hand side
LRTAP	Convention on Long-Range Transboundary Air Pollution

NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxide
OCRC	One sector models with constant returns to capital
ODRC	One sector models with decreasing returns to capital
OECD	Organisation for Economic Co-operation and Development
OLG	Overlapping generations model
PID	Multi-sector models with variable productivity of inputs used in dynamic sector
PIR	Pollution-income relation
PM	Particulate matter
PPP	Purchasing power parity
PR	River pollution
QIDI	Multi-sector models with variable quantity of inputs used in dynamic sector, in particular with endogenous investment incentives
QIDL	Multi-sector models with variable quantity of inputs used in dynamic sector, in particular with endogenous work/leisure decision
QL	Quality leader
R&D	Research and Development
RHS	Right hand side
SAEFL	Swiss Agency for the Environment, Forests and Landscape
SO_2	Sulphur dioxide
SPM	Suspended particulate matter
UK	United Kingdom
UNEP	United Nations Environment Programme
US	United States
USD	US-Dollar
WHO	World Health Organisation
WTO	World Trade Organisation

Chapter 1

Introduction

The relationship between economic growth and the environment is and probably will be, at least in the near future, one of the most important themes in economics. Both in academic discussions and in the public opinion it is often argued that gains in social welfare are only feasible at the expense of increasing environmental degradation. On account of this and to prevent an ecological disaster, environmentalists commonly postulate that growth has to grind to a halt. In the political debate, however, economic growth is still one of the principle topics. Therefore, it seems that there is a conflict of interests between economic growth and environmental protection. Recently, however, research in the field of environmental and resource economics has found evidence that increases in income do not necessarily lead to rising environmental pressure in the long run. In fact, under certain conditions economic growth may favour the environment. The literature on the Environmental Kuznets Curve (EKC) deals with this potentially non-monotonic relation.

There are several reasons why a closer investigation of the issues of *economic growth* and *environment* and of their interconnections, respectively, is worthwhile. First, economic growth by itself is an important subject. Due to ongoing growth the standard of living has improved significantly over the past centuries. This can be shown by taking income as a rough indicator for well-being. For example, in Switzerland real GDP per capita in 2004 was more than fifteen times higher than it was in 1850 and more than thirty five times higher than in 1500 (Maddison, 2003; GGDC, 2005); and the everlasting quest for growth is well documented by past and current scientific and political discussions. Second, the environment provides several important and necessary services to human well-being not captured by income: it generates amenity values, serves as a source of renewable and non-renewable resources for economic activities (e.g. energy, fossil fuels or simply water) as well as a sink for waste and pollution. Third, economic development and its repercussions on the environment are inseparable. Economic activities harm the environment inter alia in the form of air and water pollution, precarious natural resource extraction, loss of biodiversity and the greenhouse effect. For example, anthropogenic emissions of air pollutants in Switzerland have shown a drastic increase since the 1950s. In 1985, nitrogen oxides emissions had increased more than fivefold and non-methane volatile organic compounds had more than quadrupled compared to 1950. Most pollutant emissions reached a maximum between 1960 and 1985 and subsequently decreased due to the implementation of abatement measures. An exception is carbon dioxide which has not yet reached a clear turning point (SAEFL, 1995). Of course, the pollution of the environment has repercussions on the effectiveness and the availability of the described environmental services as well as on the accumulation potential of man-made capital. For example, heavy air contamination – by leading to an increased level of lead found in the blood – can negatively affect learning abilities and cause a decline in the average intelligence quotient. The negative consequences of environmental degradation on human capital formation has been observed in cities with serious air pollution, e.g. in Mexico City and Seoul (Margulis, 1992; WHO/UNEP, 1992). Finally, economic growth is not only driven by but also induces structural change and technological progress, both of which can be pollution-increasing as well as pollution-saving. In addition, increases in available income allow society, on the one hand, to spend more on abatement. On the other hand, there is also more money available to invest in potentially polluting activities. As a result of these manifold interactions, the fundamental question arises of whether economic growth without excess pollution – that is, sustainable growth – is feasible in the long run.

Despite their close interrelationship with economic growth and their importance for society, environmental issues were, for a long time, not adequately addressed in the economic literature on growth. It was not until the 1960s and 1970s that resource depletion and pollution were incorporated into growth models in the neoclassical tradition. Since this type of growth model relies on exogenously driven growth (exogenous technological progress, exogenous population growth), it is not particularly suited to the investigation of the inherent dynamic relation between economic growth and the environment.[1] With the emergence of the endogenous growth theory in the 1990s, environmental aspects could be dealt with in a framework where investments in capital stocks (physical, human and knowledge capital) are determined endogenously, i.e. as the result of economic decisions and incentives. The crucial point for sustainable development is to what extent technological progress, i.e. the accumulation of knowledge and human capital, is able to increase the efficiency of natural resources and to positively affect the substitutability between natural resources and man-made capital.[2]

Both the neoclassical and the endogenous growth models normally focus their attention on a monotonic, i.e. either increasing or decreasing, relationship between economic progress and the environment. In the last decade however, a strand of literature that focuses explicitly on potentially non-monotonic relations between growth and environmental degradation has emerged and has attracted considerable attention from theorists as well as policymakers. One of the most-used and most popular concepts with which this non-monotonic pollution-income relation can be analysed, is the so-called

[1]See Dasgupta and Heal (1979) and Clark (1990) for treatments of exhaustible and renewable resources in this context.

[2]Bretschger (1999) and Smulders (1999, 2000) provide surveys on endogenous growth models which incorporate the environment, pollution and/or natural resources.

Environmental Kuznets Curve.

The EKC literature was initiated in the early 1990s by a paper of Grossman and Krueger (1993, first published in 1991) investigating the environmental impacts of a North American free trade agreement. These authors found empirical evidence that emissions of a number of air pollutants rose with income at low levels of income, but reached a turning point around USD 5.000 (1985 PPP$) and further economic progress then led to decreasing environmental degradation. Almost contemporaneously and apparently independently, Shafik and Bandyopadhyay (1992) and Panayotou (1995, first published in 1993) reported similar results. The eventual decoupling of environmental pressure from economic growth results in an inverted U-shaped pattern between income and a measure of pollution. Following the original Kuznets Curve between income and income inequality (Kuznets, 1955), Panayotou (1995) labelled the hump-shaped pollution-income relation the Environmental Kuznets Curve.[3]

For the appraisal of the feasibility of sustainable development and for possible policy implications, the validity of the EKC hypothesis is of utmost importance. If, on the one hand, the hypothesis does not apply, i.e. if economic growth inescapably results in increasing extraction of natural resources, rising quantities of waste and emissions etc., the growth potential could be limited, as propagated by the Club of Rome and others (see e.g. Meadows et al., 1972). As a result, one could argue that economic growth must come to a halt in order to save the environment and even in order to save economic activity itself from collapse (Panayotou, 2000). On the other hand, if the EKC hypothesis applies, i.e. if an eventual decoupling of the environment from economic growth can be achieved, the reasoning could be quite different. At the extreme, some go so far as to argue that "in the end the best – and probably the only – way to attain a decent environment in most coun-

[3]Copeland and Taylor (2003) argue that this relationship should be referred to as the *Grossman-Krueger-Kuznets Curve*, since their 1993 and 1995 papers stimulated the academic interest and research in this area.

tries is to become rich" (Beckerman, 1992). As a consequence, environmental regulations – by reducing economic growth – could be counterproductive and growth enhancing policies would be the panacea for an intact environment.

Such extreme positions, however, neglect important facts. "Growth optimists" should bear in mind that the carrying capacity of the environment as a sink for waste and pollution and the natural regeneration rate of natural resources are limited. Thus, environmental degradation can cause irreversible damage once certain ecological thresholds have been crossed and economic growth can no longer act as a remedy for environmental degradation. "Growth pessimists" should keep in mind that economic growth is an inherently dynamic process and not a ceteris paribus affair. Everything that grows also changes its structure (Soubbotina and Sheram, 2000). Economic growth not only has a scale effect, but (at least) also a composition and technique effect. In other words, during the growth process, few things remain unchanged and most things change continuously; for example, the input requirements, the technologies used or the range of goods produced and services offered today are far removed from those of a century ago. For viable policy recommendations, substantiated knowledge about the factors driving the relationship between pollution and income development is decisive. So far, the EKC literature has mostly focused on empirical analysis. Yet, the driving forces underlying the inverted U-shaped pollution-income relation have still to be identified and the general validity for a broader range of pollutants remains to be confirmed.

Reviewing the huge number of empirical EKC studies one finds mixed evidence. For flow and local pollutants that have an immediate adverse effect on the environment and/or on human health the EKC pattern is mostly confirmed. For example, for sulphur dioxide and nitrogen oxides the vast majority of studies report a hump-shaped pollution income relation, even though the reported turning points differ substantially. Other examples for local, but high-risk pollutants are lack of clean water and sanitation. In these cases, the EKC (with a very low turning point) or even a monotonically decreasing pattern is almost without controversy. For stock and global pollutants such as carbon dioxide and for aggregate measures of pollution, however, the empirical evidence is less clear and less promising. Here, in the majority of cases, a monotonically increasing relationship is observed. In addition, the results are often fairly sensitive to functional form assumptions, data selection or the use of emissions versus concentrations. The special issues of *Environment and Development Economics* 1997 and *Ecological Economics* 1998 and especially the recent review article by Lieb (2003) provide comprehensive surveys of the empirical EKC literature.

Common to the empirical strand of the EKC literature is the fact that most estimations are based on ad hoc specifications and reduced form equations relating an indicator of environmental degradation to income and a vector of other explanatory variables such as openness to trade, measures of structural change, population density and geographical, i.e. country-specific variables. Due to the reduced form specification, these estimations are not able to identify the underlying mechanisms affecting the pollution-income relation. They are rather black box estimations. Usually, empirical EKC studies ex post resort to possible underpinnings of the suggested functional relationship.

A (non exhaustive) list of the given explanations includes the following aspects. (i) With rising income the demand for environmental quality increases. Lieb (2003) provides no less than three arguments in support of this proposition. First, not until the basic human needs have been met will additional resources be spent in favour of the environment. But only *rising* income makes these resources available. In addition, with rising income, non-material goods usually become more important. The amenity value of the environment constitutes such a non-material good. Second, education and, with it, environmental awareness, the fear of environmental health hazards and the concern for reduced life expectancy all increase with income. Finally, due to rising wages the opportunity costs of lost work-days caused by health problems rise with income. As a result, individuals are likely to express their changed priorities in the political progress, e.g. by voting for stricter environmental regulations. (ii) The technological aspect can encompass both increasing returns to scale in abatement and technological progress. With increasing returns to scale in abatement average abatement costs are declining. Hence, a growing economy is more likely to be able to abate an increasing part of its pollution. Technological progress – either incremental or discrete – can lead to more environmentally friendly production technologies so that the same amount of output can be produced with both less (natural) resource inputs and less waste or pollution as a by-product. Of course, technological progress is not automatically pollution-saving. Especially, at early stages of economic development, technological progress may indeed increase pollution- and resource intensities. However, with increased environmental awareness it seems not unlikely that R&D endeavours are targeted at environmentally friendly technological progress. (iii) During the growth process the structure of an economy changes. People living at the subsistence consumption level do not cause much pollution. With increasing saturation of the agricultural potential, pollution starts to increase. This increase in pollution is intensified by subsequent industrialisation. Eventually, the service sectors takes on the leading role and pollution may fall. Thus, structural change can be in favour, or to the disadvantage of, environmental quality depending on the development status of an economy. (iv) It is often argued that developed countries relocate dirty industries to poorer countries with laxer environmental regulation thereby reducing domestic pollution but not overall pollution. Since pollution is not lowered but only reallocated one can argue that only an illusion of sustainability is created (Rees, 1994). The reallocation of pollution comes inescapably to an end as soon as the poorest countries would like to source out their dirty industries. The migration of polluting production from rich to poor countries is often referred to as the pollution haven hypothesis. The counteracting factor endowment hypothesis, however, suggests that dirty production, which is usually capital intensive, is located where capital is more abundant, i.e. in developed countries (Antweiler et al., 2001). Which of these two counteracting effects dominates, is mainly an empirical question. (v) Finally, the downturn of an EKC for a specific pollutant may be the result of a substitution process between different pollutants. By reducing the emissions of a targeted pollutant, the emissions of another – not yet considered or known – may rise. As a result, the effect of the substitution on overall environmental damage can be ambiguous. Ongoing substitution between different pollutants would result in overlapping EKCs (see also Chapter 3).

Only in recent years have a rising number of theoretical papers on the EKC been published. These studies contribute to the EKC debate by identifying diverse mechanisms leading to a nonlinear relationship between economic development and environmental degradation. Within the theoretical EKC literature two major strands of papers can be distinguished. Both of them concentrate on technological aspects as the main reason for the EKC pattern (see (ii) on page 7). The first class of models stresses shifts in the use of production technologies as the main cause of the hump-shaped pollution-income relation. In Stokey (1998), the dirtiest but most productive technology is used at low levels of income. The economic reason is simply that the marginal utility of consumption is higher than the marginal disutility of pollution. Economic growth is accompanied by increasing environmental degradation. After a critical threshold is passed (due to decreasing marginal utility of consumption and increasing marginal disutility of pollution), cleaner but less productive technologies are implemented and a decoupling of economic growth and environmental degradation occurs. In Jones and Manuelli (2001) there is again a range of technologies which differ according to their production costs and their pollution intensity. The technology options and, in the end, also the pollution path depend on the type of pollution regulation. With effluent charges as the instrument of pollution control, a non-monotonic pollution path results, in particular the pollution path is N-shaped. However, if regulation restricts the choice of technology, i.e. if a minimum standard is set, pollution monotonically increases over time. In the model outlined in Chapter 3, technology shifts can, but need not be environmentally friendly.

It is rather argued that during initial phases of economic development technology shifts lead inter alia to more pollution. As the process of economic development proceeds and the individuals become aware of environmental degradation, technology shifts become more environmentally friendly.

The second class of theoretical EKC models focuses on the abatement technology, which captures the fact that pollution can be alleviated by devoting resources to improving environmental quality. In Selden and Song (1995), abatement is zero initially and starts to increase once economic development has created enough consumption and environmental damage (through capital accumulation) to merit expenditures on abatement. Similar results are presented by Chimeli and Braden (2002). Formulating a simple growth model with environmental quality (as a stock variable) the authors show that capital accumulation dominates at early stages of economic development and environmental effort is of secondary importance. Subsequently abatement becomes more relevant and attracts more resources, and economic growth declines. John and Pecchenino (1994) draw comparable conclusions using an OLG model. Again, the economy eventually switches from a corner solution with no environmental effort and increasing environmental degradation to a solution where abatement is positive and economic growth goes along with increasing environmental quality. Brock and Taylor (2004) extend the Solow growth model to include emissions, abatement and a stock of pollution. Assuming an appropriate rate of external technological progress in abatement, they show that an EKC may result along the transition to the balanced growth path. In a widely cited paper, Andreoni and Levinson (2001) focus on the characteristics of the abatement technology. Assuming that the abatement technology exhibits increasing returns to scale, the authors show that an inverted U-shaped pollution-income relation results. This approach is remarkable since it "does not require dynamics, predetermined patterns of economic growth, multiple equilibria, released constraints, political institutions, bundled commodities, irreversible pollution, or even externalities" (Andreoni and Levinson, 2001, p. 271). The EKC results solely from the interaction of the polluting economic activity and the technological properties of the abatement function.

For the sake of completeness, one should mention a third class of models which emphasises structural changes within an economy, see de Groot (1999) [see (iii) on page 7]. However, the underlying mechanism is restricted to developing countries and does not apply to mature economies, since their intersectoral shifts have been relatively small in recent decades (de Bruyn, 1997). As a result, this mechanism has not attracted great attention in the EKC literature. Moreover, it should be noted that most approaches stress the importance of a sufficiently high income elasticity of demand for environmental quality [see (i) on page 6]. It can be shown, however, that a high income elasticity for environmental quality is indeed helpful for an EKC conformable pattern, but it is neither sufficient nor necessary (McConnell, 1997). As a matter of fact, the decisive point is not that environmental quality has an income elasticity which exceeds unity (luxury good) but that its elasticity is positive (Lieb, 2002). Empirical estimations confirm that the income elasticity of environmental quality is less than unity (Kriström and Riera, 1996).

Outline of the Study

The present study is tripartite: a broader survey of growth models with trade and the environment is followed by two sections on the EKC. The first of these deals with theoretical aspects, while the second consists of an empirical investigation.

Chapter 2 tries to clarify how the sustainability of environmental quality relates to economic growth and how this relationship is affected by increasing globalisation. With the additional focus on trade, this chapter goes beyond the main objective of this study. This is important since international trade affects growth and the environment through a number of channels. The chapter consist of a comprehensive literature survey on theoretical models dealing first with economic growth and the environment, second, with trade and economic growth and finally, with trade, growth and the environment. This step-by-step procedure is indicated since few contributions directly analyse environmentally sustainable growth in an open economy context. This is remarkable since the intersection of these three issues is interesting per se and, in addition, highly policy relevant.

International trade, market integration or simply globalisation has been and still is high on the political agenda as well as being an important research topic in academia. In the public opinion, environmental problems are generally perceived to be negatively linked to the degree of globalisation. For example, the strong protests during the 1999 WTO ministerial conference in Seattle were partly motivated by concerns for the environment.

It is unchallenged that international trade has an effect on economic growth. However, the direction is ambiguous. If a country has comparative advantages in "traditional" sectors, which do not exhibit extensive positive spillovers, and thus specialises in these industries, intersectoral resource reallocation can counteract, offset or even outweigh the growth-enhancing scale and technique effects. The technique effect is based on the transnational exchange of goods, services, ideas and human resources. In this context, the process of knowledge diffusion is important. If knowledge is rather a local public good or if international knowledge diffusion is time intensive the technique effect may be limited in scope. Empirical investigations show that the importance of knowledge transfers depends inter alia on the size of a country; smaller countries rely more on international knowledge exchange (Coe and Helpman, 1995).

The effect of trade on the environment is perhaps even more complex. On the one hand, trade allows countries to export domestic pollution by outsourcing polluting industries to regions with weak or un-enforced environmental regulation. Provided that the same technology is used for production, the outsourcing has no effect on the environment. But it can trigger increases in transportation and, thus, harm the environment. On the other hand, trade indirectly affects the environment via the growth nexus. Since neither the impact of trade on growth nor the effect of growth on the environment are unambiguous, the indirect effect of trade on the environment is also not evident from the outset, but depends on the relative strength of the scale, technique and composition effects. Thus, without a clear understanding – both in theoretical and empirical terms – of the dynamic interactions between trade, growth and the environment, the question of whether trade is good or bad for the environment can not be answered.

After this broad review, the subsequent chapters focus on the relationship between environmental quality and economic growth, while the aspect of trade and globalisation plays only a minor role. This is not because trade is of secondary importance in this context but rather because the subsequent models and investigations focus on different main objectives. In particular, Chapters 3 to 6 investigate the relation between the environment and growth in the context of the EKC hypothesis. These chapters present, on the one hand, empirical evidence, but also analyse the suggested pollution-income relation within theoretical frameworks.

As stated above, theoretical EKC models either stress technology shifts or focus on an abatement technology. The model analysed in Chapter 3 belongs to the first type of EKC models. This model adds to the existing EKC literature, since it not only treats income and technological changes in general as endogenous but also endogenises the direction of technological change. In particular, after an initial zero pollution phase, economic incentives change in such a way that profit maximising firms switch from a clean to a polluting production technology. These intrasectoral shifts constitute the second new feature of the model. The direction of technological change reverses once environmental degradation has attracted the public's attention and environmental regulation is present. To avoid the pollution tax, firms find it profitable to adopt a new, clean technology. This again initiates intrasectoral shifts – this time, from dirty to clean firms. The emphasis on the significance of intrasectoral shifts caused by environmental regulation for the downturn of the EKC mirrors the reality fairly well. Empirical decomposition analyses have shown that intrasectoral shifts are more relevant with respect to explaining EKC patterns than intersectoral shifts (de Bruyn, 1997 and 2000). For example, the substantial cutbacks of nitrogen oxides and sulphur dioxides emissions in Switzerland can be attributed for the most part to the interaction of environmental regulation, intrasectoral substitution processes and the implementation of more environmentally friendly production technologies (see e.g. SAEFL, 1995).

A model of the second class, i.e. a model with an explicit abatement technology, is analysed in Chapter 4. The abatement technology employed originates from the Andreoni and Levinson (2001) paper and is characterised by increasing returns to scale. In contrast to Chapter 3, here the main objective is not to present a new mechanism which generates a hump-shaped pollution-income relation. The chapter rather expands a given basic model setup to explore two interesting issues in a dynamic context. The first objective is to analyse the economic determinants of the turning point, i.e. the income level associated with the decoupling of environmental degradation from economic development, within a theoretical framework. Not surprisingly, the degree of increasing returns to scale in abatement and the desire for a clean environment have a large influence on the turning point. The higher the degree of the increasing returns to scale in abatement and the higher the preference for a clean environment, the lower is the resulting turning point. In addition, negative external effects of polluting consumption increase the turning point, while positive external effects associated with environmental effort tend to reduce the critical level of income. The dependency of the turning point on these two market failures raises the question of how effective different environmental regulations are in correcting these market failures. The answer to this question constitutes the second objective of this chapter. Interestingly, the effectiveness of different public environment policies depends on the preference structure of the individuals. If individuals attach a high value to environmental quality, a policy measure that impedes pollution, i.e. a tax on (polluting) consumption, is more effective than a measure that is supportive of cleaning up, i.e. subsidy on environmental effort. However, the reverse is true, if individuals do not care much about the environment. The economic reason for this result is that the importance of the market failure associated with polluting consumption increases with the desire for a clean environment, while the importance of the market failure associated with environmental effort is independent of this preference parameter.

Furthermore, it is shown that the proposed model is compatible with a number of stylised facts on economic growth, i.e. the so-called Kaldor (1961) facts, and on economic growth and the environment. In particular, abatement costs are constant, emission intensity declines and the peak of absolute emissions is temporally delayed with regard to the decline in the emission intensity.

Chapter 5 deals more generally with the modelling of pollution in the EKC literature. The particular focus is on those models of the second class where net pollution is defined as the difference between gross pollution and abatement. A closer inspection of this type of pollution modelling is advisable since these models often imply that pollution becomes negative in the long run. This is, of course, a highly implausible, but far reaching prediction. If a specific model suffers from incorrect predictions in the long run, then even its results for the short and medium run can be questioned. After a delineation of two existing approaches to avoid negative pollution, a new solution is introduced. It is argued that the perpetual existence of increasing returns to scale in abatement is questionable. In fact, it is more plausible that pollution abatement becomes relatively more resource intensive as the last speck of pollution must be tackled or as the potential for learning-by-doing has been largely exploited. On the basis of these considerations, the concept of fading increasing returns to scale is proposed. Basically, the abatement technology exhibits increasing returns to scale but their degree ebbs away with increasing environmental effort. With such a specification of the abatement technology non-negative pollution levels can be achieved also in the long run.

In the last chapter of this study, an empirical investigation on Environmental Kuznets Curves for Germany is presented. Its fundamental questions reads: Do Environmental Kuznets Curves exist for a single country? Thus, in contrast to the majority of empirical EKC studies, the estimations are based on time series data and not on a cross-section of countries. Albeit the EKC is sometimes regarded as a cross-section concept, a time series analysis seems to be more than warranted. The following arguments and findings are supportive of this position. An EKC found by cross-country estimations could result from the coexistence of two different and independent relationships: a monotonically increasing pollution-income relation in poorer countries and a monotonically decreasing relation in richer countries (Vincent, 1997). The combination of these two relations would result in a pseudo EKC. In other words, pooling heterogeneous countries in one and the same panel can bias the estimates (Dijkgraaf and Vollebergh, 2005). Finally, is has been shown that even for relatively homogeneous countries the estimated pollution-income relations might differ substantially. Analysing nitrogen oxide and sulphur dioxide, List and Gallet (1999) report fairly heterogeneous turning points for the different US states. In the case of nitrogen oxide, the highest is more than fifty three times higher than the lowest. The corresponding figure for sulphur dioxide is twenty three. The problem of the homogeneity assumption within a broad spectrum of countries can be summarised in a nutshell by a quotation of Harberger (1987): "What in the world do Thailand, the Dominican Republic, Zimbabwe, Greece, and Bolivia have in common that merits their being put in the same regression analysis? Answer: For most purposes, nothing at all."

The estimations of Chapter 6 are based on emissions data of eight different air pollutants for Germany. The results of the traditional reduced form regressions indicate a hump-shaped pattern only for nitrogen oxide and ammonia. The other six pollutants, however, do not show clear-cut and significant results. Besides the use of time series data a second feature of the estimations in this chapter is noteworthy. In order to deal with the non-stationarity of the variables used, a modified error correction model is employed in a second step. The modification concerns the supposed underlying long-term relationship. To give consideration to the EKC hypothesis this relationship is assumed to be non-linear, i.e. either quadratic or additionally with a cubed term. Again estimations are run for all eight pollutants and in different variations, i.e. with and without additional regressors beside income. Even though the results are more supportive of the EKC hypothesis, the above stated fundamental question cannot be conclusively answered. The overall picture of the estimations is somewhat fuzzy. However, since the results of cross-country and panel data estimations cannot be confirmed without restrictions, the investigations of this chapter back up the demand for further research with regard to the questions raised.

Chapter 2

Sustainable Growth in Open Economies*

2.1 The Dynamic Perspective: International Sustainability

2.1.1 Introducing Dynamics

International environmental economics can be conducted both in a static and in a dynamic mode. This chapter introduces the dynamic approach view. We analyse the impact of international trade and the natural environment on long-term economic development. In the literature, there are hardly any contributions which cover environmental economics, trade, and growth at the same time. Most of the papers in this field concentrate either on the interaction between (i) international trade and the environment (for a survey see Schulze and Ursprung, 2001a-c), (ii) economic growth and the environment or (iii) trade and economic growth. To obtain a comprehensive view of the intersection of all three issues, we proceed in the following manner. In the first section, we focus on economic growth and the natural environment by

*Published in Schulze and Ursprung (2001). This chapter represents joint work together with Lucas Bretschger (ETH Zurich).

introducing the most important concept in this field: sustainability. Section 2.2 demonstrates how endogenous growth theory identifies sustainable development paths. We present the predictions of different growth models, which also portray changes in the natural environment. The international aspects are introduced by considering open economic growth models in Section 2.3. Building on the insights of modern growth theory, we discuss the literature which analyses the impact of trade relations, trade policy, and the international division of labour on the sustainability of growth in Section 2.4. Empirical results are presented in 2.5. The concluding section summarises the results and identifies important issues which emerge from the discussion and remain for future research.

2.1.2 The Sustainability Paradigm

The "Brundtland report" defines sustainable development as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (World Commission, 1987). Development, thus, includes not only rising aggregate consumption or output, but also environmental quality, social factors, and the distribution of income. Taking such a broad view, economic theory can make substantial contributions to several focal points. The most important concept in economics is individual welfare, which is usually captured with the help of utility functions. Realistic utility functions include not only consumption but also environmental quality. In a dynamic set-up, the final objective of any normative theory of economic growth is the long-term development of individual utility.

If the above definition of sustainability is interpreted in economic terms, a sustainable growth path can be characterised by non-declining welfare between generations, where welfare is measured as average individual utility (see Pezzey, 1989 and Bretschger, 1998c). By demanding constant or increasing welfare over the long run, sustainability is more than survivability, which only requires consumption to be kept above some subsistence minimum. Both fairness and efficiency criteria are crucial ingredients of sustainable growth paths. Efficiency considerations, which underlie the positive and normative view of environmental policy, are, of course, at the heart of economic theory. Concerning fairness, i.e. the intra- and intergenerational distribution of income, the main contribution of economics is to investigate the relation between ethical constraints and the development of welfare.

2.1.3 Fairness Criteria

One should distinguish carefully between efficient allocations of resources – the standard focus of economic theory – and socially desired allocations that may reflect intergenerational as well as intragenerational equity concerns. Due to physical limits and ethical constraints on resource use, a sustainable development path may not be the same as the efficient path predicted by standard economic theory (see Pezzey, 1989 and Toman, 1994). For example, it might be optimal from today's perspective to use considerable amounts of natural resources. But this resource use might not be fair for future generations if it causes individual welfare to decrease in the far future (see Beltratti, 1996). Furthermore, it should be noted that incorporating environmental values in decision-making per se will not bring about sustainability unless each generation is committed to transferring to the next sufficient natural resources and capital assets to make development sustainable. Put another way, the problem of intergenerational equity must be viewed as an issue of ethics that is distinct from economic efficiency in the Pareto sense (see Howarth and Norgaard, 1992). For sustainability, one has to take the distribution of welfare between present and future generations into account. One possible solution is to alter the welfare criterion, which is the guideline for optimisation today. Chichilnisky (1977) proposes a welfare function which is a convex combination of a discounted sum of instantaneous utilities and a minimum condition for future utility levels. A more straightforward procedure is to include the additional element of intergenerational fairness in optimising by excluding all efficient development paths which lead to declining average utility in the future. To do so, the sustainability criterion is imposed as a prior constraint on the maximisation of individual utility. Consequently, each successive generation ensures that the expected welfare of its children is no less than its own perceived well-being (see Howarth, 1995).

2.1.4 Focusing on Capital Stocks

While individual welfare considerations are usually restricted to flow variables, some authors argue quite forcefully that capital stocks should be the primary focus in the debate. Emphasising the quality of the natural environment, sustainability is interpreted as "requiring some constancy in the stock of natural environmental assets" (see Pearce et al., 1990). In this context, "weak" and "strong" sustainability have become widely used terms. Weak sustainability means that any form of natural capital can be run down, provided that proceeds are reinvested in other forms of capital, for example man-made capital. Strong sustainability, however, requires that the stock of natural capital should not decline (Pearce and Atkinson, 1998). In this context, one distinguishes between the requirement to conserve every single natural resource and the requirement to conserve an aggregate natural capital stock which leaves room for certain substitution possibilities.

In order to put the theoretical principles of strong sustainability into practice, one can lay down two main rules for the use of renewable natural resources. First, the harvest rates should equal the regeneration rates. Second, the waste emission rates should be in line with the natural assimilative capacity of the ecosystem. For non-renewable natural resources, the problem is quite different. A strong management proposal is formulated by Turner (1988). He argues that talking about sustainable use of a non-renewable resource is useless because any positive rate of exploitation will lead to the exhaustion of the finite stock. However, it should be noted that the effect of exhaustion of certain stocks on welfare is by no means obvious; at least, it is not directly given for all natural resources. It might be that utility remains constant even with a decreasing stock of certain resources or that several (very special) resources do not have an impact on utility at all. Nevertheless, the following arguments in favour of strong environmental sustainability are relevant (see Pearce and Atkinson, 1998). First, there is uncertainty about the value of the elasticity of substitution between natural resources and man-made capital. Second, there is an asymmetry between the different types of capital with respect to reversibility: once certain critical natural capital stocks are lost, they cannot be re-introduced. Put differently, a constant stock of certain natural resources can be necessary because natural threshold and irreversibility effects may severely limit the trade-offs that can be allowed between different resources without threatening sustainability (see Pearce et al., 1988 and 1990). Third, the scale effects from the loss of critical natural capital are not known and, finally, consumers have an apparent "loss aversion" that arises when certain natural resources are depleted.

The arguments in favour of strong sustainability given above should make us more cautious about depleting natural capital, but the issues raised do not add up to a complete justification for implementing this criterion. Pezzey (1989), for example, expresses that trade-offs between natural and man-made resources can, in principle, be calculated if appropriate weights are used. A "quasi-sustainable" use of non-renewable resources can be achieved by limiting their rate of depletion to the rate of creation of renewable substitutes (see Daly, 1990). The concentration on natural capital stocks has been challenged because this view does not consider intertemporal efficiency. According to Dasgupta (1995), any stock concept is a "category mistake" because it mixes up the determinants of human well-being and the constituents of well-being. This means that capital stocks may influence welfare directly or indirectly but they are not the final argument in the utility function.

2.1.5 Sustainability in International Perspective

The final goal expressed by the notion of sustainability is non-decreasing welfare between generations. Taking the special attributes of natural resources into account, it is appropriate to supplement this general goal with an intermediate target concerning certain requirements for the state of the natural environment. The higher the probability of irreversibilities and the larger the uncertainties about aggregate costs of damage, the safer the minimum standards for the respective natural capital stocks should be (see Bretschger, 1998c).

Allowing for free trade between the economies and considering international externalities does not alter the basic concept of sustainability as a general guideline for policy. It seems to be straightforward to require sustainable development for all the regions of the world, which adds up to sustainable development for the world as a whole. What does change, however, is the way sustainability can be achieved. The international division of labour can decrease but also, under unfavourable circumstances, increase the difficulties in reaching sustainable development. On the one hand, free trade may allow natural resource use to be diminished in the economies where the associated costs are the lowest internationally. On the other hand, free trade might intensify inefficient resource use in certain countries. If, for example, international prices of a free access natural resource are higher under free trade than under autarky, trade may cause an overuse of certain natural resources. A case in point is, for example, tropical timber (see Barbier, 2001).

Simple maximisation of the utility of present generations will generally not be sufficient to reach sustainable development paths. This is true both for a single country as well as for the decentralised world economy as a whole. Present value maximisation incorporates neither the existence of positive and negative externalities nor the sustainability constraint. It is, therefore, useful to distinguish between three possible types of development paths: paths that are reached under free market conditions, paths that materialise when all external effects are internalised by economic policy ("optimal paths"), and paths that are sustainable, that is, exhibit non-declining individual utility between generations. The free market and/or the optimal paths may be sustainable in certain cases, but not under all conditions. The following sections focus on the different links between growth, natural resource use and trade in detail. Important issues not dealt with in existing literature are pointed out in the last section of the chapter.

2.2 Natural Resources and Economic Growth

2.2.1 Growth and Sustainability

In this section, we identify the relevant issues which arise when the concept of sustainability is introduced into several theories of economic growth. In particular, we aim at analysing the interactions between the state of the environment and the achieved growth paths. In older theory of economic growth, the long-term growth rate is determined exogenously. Only the adjustment growth to the steady-state can be explained by this theory. The emphasis is on the accumulation of physical capital which is subject to diminishing returns. In recent models of endogenous growth, however, the long-term growth rate is explained endogenously, that is, it depends on the production technique, preferences, and fiscal policy. Economic decisions carried out under market conditions induce technical change and endogenously affect the stocks of all kinds of capital, such as physical, human, public, and knowledge capital. The mutual relation between economic growth and the environment can be analysed as well. The relationship between natural environment and long-term growth is important since there is only little gain in speculating about hypothetical development paths that have no factual basis. Similarly, any intuition about the consequences of discounting future well-being is elusive, unless feasible development paths can be identified (see Koopmans, 1965).

Thus, a profound study of sustainable growth is not possible without a sound theory of economic growth, in particular, of endogenous growth.

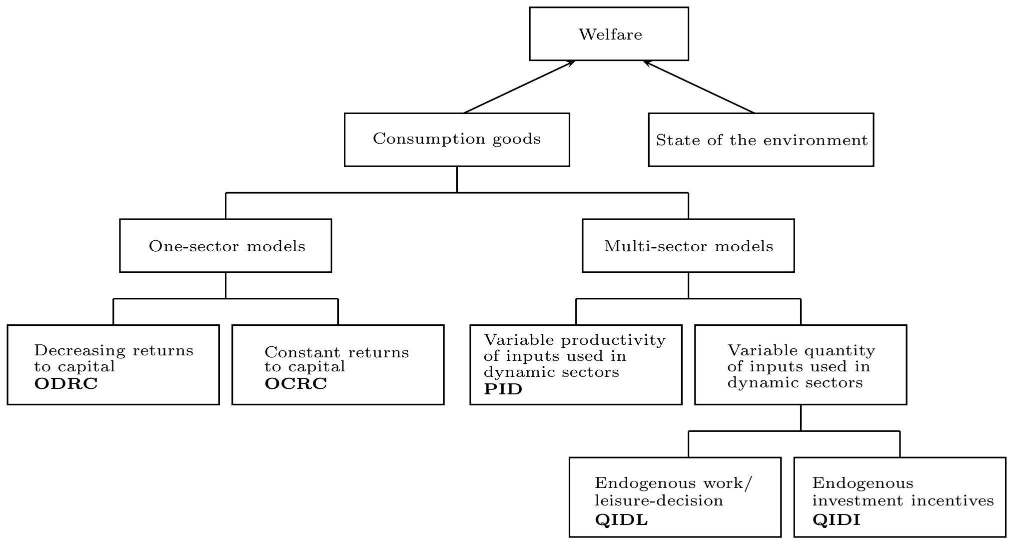


Figure 2.1: Types of growth models with natural resources

In the following, the different growth models which consider the effects of natural resources are categorised in Figure 2.1. For each model, the relation between growth and state of the environment will be analysed. The figure shows that the final objective of the agents portrayed by any economic growth theory is (individual) welfare. There are, in principle, two channels which transmit the influence of the environment on welfare. First, there is a direct impact of the state of the natural environment on personal well-being, which applies, for instance, to the cases of air quality or the amenities of the landscape. Here, it is obvious that ceteris paribus a better environment increases welfare. Second, environmental quality and natural resources affect the production process and by this, indirectly, future consumption possibilities. The influence of the environment on the production sector can be modelled in different manners which we will present in the following. We use the term "capital" for accumulable (man-made) capital and the terms "natural resources" and "pollution" for the influence of the environment on the production sector.

2.2.2 Applying Different Growth Models

Depending on the assumptions about the marginal productivity of capital, long-term growth is either an exogenous or an endogenous variable in the model. Postulating sufficiently decreasing returns to capital, the growth process peters out in the long term. The assumption of constant returns to capital, however, renders endogenous growth in the long term feasible; it keeps savings and investment incentives at a constant (positive) level. In addition, one can distinguish between one-sector models and multi-sector growth models. In one-sector models, the production technique is the same for consumption and investment goods. Multi-sector models usually have a dynamic sector, for example, research and development or education, and one or more static sectors for the production of consumer goods. In these models, the growth rate depends on the characteristics of the dynamic sector. Multi-sector models which include natural resource effects can further be divided into models where environmental quality directly alters the productivity of inputs in the dynamic sector, and models where the quantity of inputs used in the dynamic sector is affected. The latter is portrayed either by incorporating leisure into the model, which allows for more or less labour being used in the dynamic sector, or by varying investment incentives, for example, in research and development (R&D), which alters the quantity of inputs used in the dynamic sector.

In the following, we summarise the relevant literature and provide an intuition for the behaviour of the archetype models. We show under which assumptions and conditions (positive) endogenous growth can be realised while the environmental quality does not deteriorate. Taking the limited pretension of this strand of literature into consideration, such a development can be called sustainable. In addition, the focus will be on the dynamic effects of environmental policy. After the general discussion, we will study the growth effects of a "green tax reform" in particular.

2.2.3 Model Type ODRC

A traditional approach to modelling the growth process is by way of a **o**ne-sector model with **d**ecreasing **r**eturns to **c**apital (ODRC). The most prominent representative of this class is the neo-classical growth model. As a consequence of the decreasing returns to capital, growth can only be explained in the medium term, that is, only in the phase of adjustment to the long-term steady state. In the long term, the growth rate is determined by exogenous technical parameters (i.e. by exogenous labour-augmenting technical progress). This modelling approach in particular encompasses the standard "Solow"-model with a constant savings rate and the so-called "Ramsey-Cass-Koopmans"-model, which is based on intertemporal optimisation. Using the "Ramsey-Cass-Koopmans"-approach, the state of the environment can be included in the utility function, so that abatement activities become desirable. A rise in the concern for the environment can be expressed by an increased weight of the environment in the utility function or by the introduction of taxes to internalise the negative externalities of pollution. According to the assumptions regarding the production function, more environmental care does not affect the growth rate in the long run in this setting. But environmental policy leads to a different steady-state. If the use of capital generates pollution, the environmental policy induced steady state is characterised by a lower capital intensity. This is due to an increase in the price of capital relative to the other production factors. This price increase is a consequence of the environmental policy, which is aimed at a less polluting production process, that is, a taxation of the polluting production factors, namely capital (see Gradus and Smulders, 1993).

Now assume, alternatively, that the natural environment has an impact on capital formation, since a natural resource is used in the production process. With increasing exhaustion of this natural resource, its price is assumed to rise such that the quantity used in production decreases over time. This is the standard assumption given that the natural resource stems from a fixed stock, that is, an exhaustible (non-renewable) resource. If, in the one-sector approach, all inputs, notably capital, natural resources, and labour, are treated symmetrically, growth is only sustainable if the elasticity of substitution between the inputs exceeds a critical value (see Bretschger, 1998a). With a constant savings rate as in the "Solow"-model, the critical value is exactly equal to unity. For the corresponding Cobb-Douglas production function, Stiglitz (1974) shows that a necessary and sufficient condition for a constant level of consumption (with no technical change) is that the share of natural resources is less than the share of capital. Formulated in terms of the required savings, the consumption level can be sustained exactly, provided all returns on the natural resource are used for capital accumulation. This is the so-called "Hartwick-rule". However, if savings are realistically assumed to depend on interest rates as in the "Ramsey-Cass-Koopmans"-model, the critical value must be strictly larger than unity. This is necessary to obtain constant incentives for investments, which means constant returns to capital when the quantity of capital is increased over time. A value that is larger than unity leads to a decreasing share of natural inputs and an increasing share of capital of total income.

The prerequisite of elasticities of substitution between natural and other inputs being larger than unity has attracted severe criticism. Many authors have argued that physical laws limit the extent to which physical capital can substitute for the natural capital stock. On the other hand, not only physical capital but also human and knowledge capital should be considered. For the last two capital components, the restrictions of material balances do not apply (see Smulders, 1995a). In addition, in a multi-sector model further substitution possibilities emerge, namely the substitution between sectors, which results in a new determination of the critical values for the elasticity of substitution (see the QIDI-models below).

2.2.4 Model Type OCRC

Up to now, we have seen that if we assume decreasing returns to capital one cannot explain the long-term growth rates. From now on, we will therefore assume **c**onstant **r**eturns to **c**apital to obtain an endogenous growth rate. In the **o**ne-sector approach (OCRC), this specification leads to the so-called "Rebelo"-model of economic growth theory, which, in our case, is supplemented by the natural resources and pollution aspects. Again, the use of capital is assumed to be polluting and the state of the environment is included in the utility function, so that abatement activities are desirable. As a consequence of the one-sector structure, no resource-saving knowledge can be generated and therefore no transition to a less polluting production process is possible. There is just one production factor in the model, namely capital. The term "capital" is sometimes interpreted in a broad sense, so as to include physical, human, and knowledge capital. In the "Rebelo"-model, however, capital is introduced as an aggregate variable so that we have no explicit substitution possibility for any form of input. Income can be used for consumption, capital investments or cleaning activities. Let us first assume that factor productivity is not affected by environmental quality. Under the specification of this model, a decrease in pollution due to a tighter environmental policy (or an exogenous rise in the disutility of pollution) gives rise to more cleaning activities and, therefore, to a crowding-out of consumption and investments. The crowding-out of investments reduces the growth rate; therefore, a negative relation between growth and environmental care emerges (see Gradus and Smulders, 1993). However, welfare is higher in the new steady-state because of a better environmental quality.

The dismal consequences of this model will no longer materialise as soon as there are productivity effects of natural resources or substitution possibilities in production. If one gives up the assumption that the environment does not affect the factor productivity, a different result can be obtained. As before, more concern for the environment leads to more abatement activities and, consequently, to a better environmental quality. But now, assume that a cleaner natural environment implies an increase in the productivity of capital. This positive effect boosts the growth rate. If the positive effect is high enough, the negative crowding-out of growth-generating investments brought about by abatement activities can be offset. Thus, an increasing growth rate and a cleaner environment can be reached under these assumptions (see Smulders and Gradus, 1996).

Aside from the productivity effect, the substitution effect between several input factors is another possible ingredient in the one-sector approach. Assume a production sector with capital, natural resources, and labour as inputs, where the assumption of constant returns to capital still holds ceteris paribus. (This is an extension of the "Rebelo"-model.) The resulting production function has increasing returns to scale. But this property does not change the results on input substitution as compared to the case of decreasing returns to capital. The reason is that a decreasing input of the natural resource affects the return on capital negatively such that the ceteris-paribus condition does not hold in this case. Regarding the effects of capital accumulation which is accompanied by a decrease in the use of natural resources, the return on capital decreases over time. Thus the behaviour of the ODRC-model carries over to the OCRC-model in this case.

To conclude discussion on one-sector models, one can summarise that a direct connection between the long-term growth rate and the state of the environment only exists if constant returns to capital are assumed. Whether a cleaner environment or a more moderate use of natural resources, respectively, is compatible with an increasing growth rate depends on whether one assumes factor productivity gains from a better quality of the environment.

2.2.5 Model Type PID

We now turn to multi-sector models. First, we analyse models in which the environment may alter the **p**roductivity of the **i**nputs used in the **d**ynamic sector (PID) where growth is generated. Many authors focus on the so-called "Uzawa-Lucas"-model. This model has a production sector producing consumption and investment goods and an education sector, where skills (i.e. human capital) are generated. Growth is driven by human capital accumulation, that is, without advancements in the education sectors, growth peters out. As before, assume the use of capital to be polluting. What is the effect of environmental policy, for example, of the internalisation of pollution, in this case?

In this simple setting, environmental policy influences only the marginal value of physical capital but not the efficiency of human capital in the education sector. Therefore, the growth rate of the economy remains unaffected by environmental policy. However, the capital intensity decreases in the steady-state due to changed relative prices of capital components. As in the one-sector case, the price increase is a consequence of the taxation on the polluting production factors. The only direct way to stimulate growth is a rise in the productivity in the education sector. A further possibility (which is in fact valid in all growth models) would be a decline in time preferences. This applies here because lower time preferences lead to more education and therefore to an increased output in the future. But normally, the size of the discount rate is not explained by economic theory, that is, it remains an exogenous variable.

If, however, one extends the "Uzawa-Lucas"-model in the sense that pollution also affects learning abilities, that is, the marginal returns to education, the effects of environmental quality on the growth rate are different. Assume pollution to decrease learning abilities (which has been observed empirically in regions with heavy pollution of the air, for example in Mexico City). Consequently, investments in human capital become less efficient with higher pollution. Similarly, it can be assumed that the depreciation rate of human capital is increased by higher pollution. As above, more environmental care leads to more abatement activities and to a better environmental quality. But now, the output per unit of human capital rises as a consequence of environmental policy which stimulates human capital accumulation and, thereby, the growth rate of the whole economy. This positive effect can normally not be offset by the crowding-out of investments due to more cleaning activities. The result is a higher growth rate and less pollution (see Gradus and Smulders, 1993).

Another version of the "Uzawa-Lucas"-model does not include physical capital at all. Moreover, in this pure human capital version, growth is driven by human capital accumulation. Pollution is assumed to have a negative impact on both the productivity in the final goods sector and the acquisition of skills. In other words, the engine of growth is again impaired by pollution. Positively formulated, a cleaner environment due to higher pollution taxes or more concern for the environment leads to an increased productivity in the learning sector and, therefore, to a higher growth rate (see van Ewijk and van Wijnbergen, 1995).

Now let us consider the Bovenberg and Smulders (1995) model in which the environment affects the production function of consumption goods in two different ways. Environmental quality is, on the one hand, modelled as an input factor. It is introduced as the stock of natural capital which provides productive services to economic activities. The stock of natural capital has a natural regeneration rate, which increases the stock. On the other hand, the stock is diminished by the use of natural resources in production (or by "pollution", respectively). As a further element of this approach, resource-saving technologies can substitute for the use of natural resources (or for "pollution"). These technologies are generated in the learning sector. Also, the learning sector is using natural resources as an input.

Two different cases can then be distinguished: one in which only the environment (meaning the natural capital stock) enters the utility function and another in which the environment enters the production function too. In the first case, more concerns for the environment give rise to a declining productivity of both kinds of man-made capital, that is, physical capital and resource-saving knowledge. This is because natural resources and man-made capital are substitutes, so that a decline of one input decreases the productivity of the other. As a consequence, we have falling rates of return on investments and a declining growth rate. This effect varies positively with the influence of natural resources on production of consumption goods and negatively with the influence of physical capital on production in the learning sector. In the second case, lower resource use exerts a strong positive impact on factor productivity in final goods production in the long run. This effect varies positively with the production shared of natural and physical capital, and negatively with the impact of natural resource use on capital productivity.

An extension of this first approach is to assume that natural resources are essential for the production of consumption and private capital goods as well as for the production of public knowledge. In this case, a tighter environmental policy results in a reallocation of economic activity away from the pollution-intensive private goods sector towards the production of knowledge, which is assumed to be a substitute for pollution. Furthermore, anticipating the future benefits of a better environment and a increased productivity of accumulated assets due to better public knowledge, consumers demand more final goods. These two effects result in a fall of private capital accumulation. In the long term, however, more and more environmentally friendly technologies are developed, so that the private goods sector recovers gradually. Taken together, the tighter environmental policy leads to a higher rate of return and a higher growth rate which is sustained by higher investments in private capital, knowledge capital, and natural resources; for transitional effects see Bovenberg and Smulders (1996). In a special case of this model, the environment is assumed to be a pure investment good. Using this specification, the long-term behaviour does not change, but growth also rises in the short term. Due to rapidly accruing productivity gains, the crowding-out of investments in man-made assets can be offset immediately (see Smulders, 1995b).

2.2.6 Model Type QIDL

In the previous section we have looked at multi-sector models in which the influence of natural environment on the production sectors and, therefore, on the growth rate occurred through factor productivity changes. As already mentioned, there is another way to model growth effects of the environment. We now assume that the production sector and the growth rate are influenced by environment-induced changes in the **q**uantity of **i**nputs used in the **d**ynamic sector of the economy.

In many growth models, the available working time of the individuals is constant, that is, a fixed labour supply is assumed. For example, in the Uzawa-Lucas approach, time can only be spent either on the production of final goods or on studying, but leisure is disregarded in this model setup. Including **l**eisure in the model (which leads us to the QIDL-model) means that the available time for productive activities is no longer constant, since leisure is not productive. However, leisure enters positively in the utility function.

The question now arises as to whether the introduction of leisure affects the time allocation. In particular, we have to ask if a tighter environmental policy, for example, the introduction of a pollution tax, increases the time spent in education. A higher pollution tax leads to more abatement activities which requires resources from the consumer sector. Decreasing consumption leads to higher marginal utility of consumption. To equate marginal utility of leisure and of consumption, households choose to increase studying time and to decrease leisure. Put differently, individuals aim to counteract reduced consumption possibilities by reducing leisure time, while, indeed, spending more time studying, which increases human capital accumulation and the growth rate. Therefore, one conceivable result of this model setup is that a tighter environmental policy has a positive impact on economic growth (Hettich, 1998).

2.2.7 Model Type QIDI

Another mechanism of varying **q**uantities of **i**nputs used in the **d**ynamic sector works through **i**nvestment incentives (QIDI). In multi-sector models man-made capital is not only an input into production but also an output of specific sectors in an economy. This fact has a large influence on the sustainability results. By modelling this double role of capital, one can show that it is the substitution between primary inputs (such as labour and natural resources) as well as the substitution between different sectors of the economy that matter for long-term development. To derive this effect, it is assumed that the dynamic R&D-sector is relatively extensive in the use of natural resources.

Regarding the incentives to invest in the capital-producing sector, that is, in the R&D-sector which produces knowledge capital, there is a cost and a reward effect. Following an increase in the price of natural resources, costs in the dynamic sector decrease, provided that labour is a bad substitute for the natural resource (see Bretschger, 1998a). So, viewed from the cost effect, a low elasticity of substitution between primary inputs does not prevent the economy from remaining on a sustainable growth path. In standard growth models, which use monopolistic competition to determine the rewards of the dynamic sector (e.g. R&D), rewards of investments remain unaffected by natural resources (see Bretschger, 1998a). If, however, capital (e.g. knowledge capital) can substitute for natural resources, the rewards for investments increase with rising prices of natural resources. In this case, the positive incentive effect of rising resource prices on capital investments is strengthened.

Thus, it can be demonstrated that, while in a one-sector set-up of the model, growth is only sustainable if the elasticity of substitution between natural and other inputs is larger than unity, in multi-sector models the elasticity may be smaller than unity in some sectors without making growth unsustainable. This suggests that the trade-off between long-term economic development and the protection of the environment is, under realistic assumptions, smaller than commonly postulated.

2.2.8 Green Tax Reform and Growth

A widely discussed issue today is the combination of an increase in environmental taxes and a parallel decrease in taxes on other factors, the so-called "green tax reform" [for an extensive survey of open economy models analysing the effects of such a tax scheme, see Smulders (2001)]. In the contribution of Bovenberg and de Mooij (1997), there are two channels through which an environmental tax reform may yield not only an improvement in the environment but also a higher growth rate, that is, a so-called "dynamic double dividend". The first channel is effective due to a positive environmental externality on production; the second channel operates by a shift in the tax burden away from the return on capital accumulation towards profits. The second channel, contrary to the first, only works if the elasticity of substitution between pollution and other inputs is not too high, so that the base of the pollution tax is inelastic.

Considering several taxes simultaneously, Hettich (1998) and Hettich and Svane (1998) investigate the interactions between public finance, endogenous growth, and the environment. Whereas in both models human capital accumulation in the education sector is assumed to be the engine of growth, Hettich (1998) treats leisure as an endogenous choice variable and Hettich and Svane (1998) assume leisure to be given exogenously. Without governmental intervention in favour of natural resources the effect in both models is that pollution is too high, too few abatement activities are undertaken, and final goods production is too capital intensive.

In the endogenous leisure model, a pollution tax, contrary to a tax on consumption, capital or labour, leads to increased long-term economic growth as well as increased welfare as long as the tax is below the Pigouvian level. One reason for the positive effect of the pollution tax on growth is that leisure is reduced in favour of studying time. Consequently, more human capital is accumulated and the growth rate increases. In the model with given leisure, factor income taxes reduce growth. A pollution tax, however, leads to a stimulation of the growth rate if the productive spillovers of a better environmental quality are high enough. Due to the increasing quality of the environment, welfare is improved as long as pollution exceeds the optimal level.

If the labour market is added to the model, one can analyse not only the interactions between environmental quality and long-term growth, but also the employment effects (see the approach of Nielsen et al., 1995). These authors assume a further (rather special) ingredient, namely that the productivity of pollution abatement activities varies negatively with environmental quality. Two kinds of exogenous changes are considered. First, if there is a shift towards more concern for the environmental quality, the optimal pollution tax rate increases, whereas the optimal level of abatement expenditures decreases due to the falling productivity of pollution abatement activities. The employment effect is ambiguous, that is, it depends upon the tax regime. Second, the tax regime may shift from a command-and-control tax regime, under which the firms can pollute the environment free of charge up to the limit given by the standards, towards a pollution tax regime, under which environmental property rights are assigned to the public and all firms are forced to pay for the services from the environment. This change implies an improved efficiency of environmental regulation. As a consequence, both the growth rate and consumer welfare increase, without any adverse effect on environmental quality. In addition, there are employment gains since the pollution tax revenues allow a reduction in the labour tax.

2.3 Development in Open Economies

2.3.1 Trade and Dynamics

Trade theory is mainly concerned with static models. If capital accumulation is introduced, a middle-term adjustment process to the steady-state with the help of the neo-classical growth model can be analysed. Another possible direction in research is to look at the consequences of exogenous growth on the foreign trade position of a country. Here, how international trade is affected by economic growth abroad (increasing consumption demand from foreign economies) or by domestic growth (better production conditions in the domestic economy) can be studied. But as in the closed economy, the prediction of sustainable development paths in open economies requires a theory of endogenous growth.

As has become clear in the last section, endogenous growth requires constant returns to capital. Constant returns are normally motivated by the existence of positive spillovers, for example, knowledge spillovers in the sense of learning-by-doing. Furthermore, spillovers are assumed to increase with the extent of economic activity. Taking the example of research, this means that current research is the more productive the more research has already been carried out in the past (see Romer, 1990). Put differently, the greater the knowledge capital is, the greater the advantage for future additions becomes. The same is true for other capital components like human capital and public infrastructure. Therefore, it is decisive for the international division of labour in what way the economies of scale of a country can be shared by the other countries, and inversely, in what way each individual country can participate in the economies of scale of the other countries (see Grossman and Helpman, 1991).

2.3.2 Scale and Reallocation Effects

Since the possibilities to exploit scale effects are broader in the international context, new growth chances arise from the establishment of outward relationships. The international transmission of knowledge certainly provides such prospects. If knowledge arises as a side product of different kinds of investments, the size of the geographical spread of the knowledge spillovers is important for the dynamics of open economies (see Young, 1991; Ben-David and Loewy, 1998; Bretschger, 1997). Positive spillovers are also effective in the accumulation of other factors like public services and human capital. Typically, however, the effect of public services is limited to the geographical region which belongs to the political unit considered. Human capital is internationally mobile only if skilled labour migrates over the country boundaries. In reality, the share of internationally mobile skilled labour is small in comparison to the total amount of skilled labour. If economies of scale remain partly or totally limited to a country or a region, distinct specialisation patterns arise in the interregional and international division of labour. A country or region can gain economies of scale in special industries which are not or barely existent in other places. By analysing the history of clearly defined regions of economic specialisation, one may be able to show how such specialisation, for example, in financial services, heavy industry locations, high-tech commodity production, etc., is generated via accumulated scale effects. The beginning of such a development can often be traced to rather accidental circumstances.

Another crucial point in the transition from autarky to free trade is the trade induced change in the intersectoral factor allocation (see Bretschger, 1999). After the opening of an economy to free trade, a country with comparative advantage in traditional production will specialise in this field. In contrast, countries with comparative advantage in research or in high-tech production will use more resources in these sectors (while becoming a net-importer of traditional goods). If the positive spillovers are of different intensity for the different sectors and, additionally, are not fully international in scope, resource reallocation caused by trade has an impact on growth. If the learning-intensive sectors which generate extensive spillovers increase in size, the growth rate rises, while in the opposite case, the growth rate decreases. Trade thus might, under unfavourable conditions, decrease the growth rate (see Grossman and Helpman, 1991 and Bretschger, 1997).

To evaluate the consequences of international trade for sustainability, the environmental dimension needs to be added. In the following section we therefore introduce pollution and the use of natural resources into open economy growth models.

2.4 Trade, Growth, and the Environment

In this section, we look at models of open economies which take the environment and long-term growth into account. In particular, we are interested in the interactions between trade, economic growth, and the environment. Thus, the link between the environment and growth on the one hand and between trade and growth on the other hand need to be considered simultaneously. Obviously, this is a challenging subject and only some of the immanent issues have been dealt with so far. In this section, we will discuss the existing literature and consider the remaining issues in Section 2.6.

2.4.1 Small Open Economies

A representative model of a small open economy is constructed as follows (see Elbasha and Roe, 1996): there are two final output sectors and a research and development sector; output is produced with primary inputs and differentiated intermediate goods . The output of the R&D sector consists of patents which contain the knowledge to produce new intermediate goods. Pollution can either be assumed to be caused by final output or by differentiated intermediate goods. The small open economy grows at a rate which is different from the world growth rate because of somewhat specific assumptions, such as the assumption of no trade in intermediate goods. In the model, trade alters the relative prices of final goods and, thereby, the dynamic behaviour of the whole economy.

In accordance with the R&D-models of endogenous growth of the closed economy, one finds that, in this setting, long-term growth increases with a country's endowments in primary factors. This is due to the fact that a larger resource base leads to a larger research sector and increased spillovers. Moreover, the growth rate increases with the degree of market power of patent holders since this means increasing incentives for R&D-investments. The effects of environmental policy on growth depend on the elasticity of intertemporal substitution of consumption. If this elasticity is greater than unity, growth of output is reduced after a tighter environmental policy has been implemented. If this elasticity is less than unity, a tighter environmental policy promotes growth. Finally, if it is equal to unity (logarithmic utility function), growth remains unaffected. A high elasticity of substitution means that agents find it optimal to choose a low level of environmental quality (see Aghion and Howitt, 1998). According to empirical literature, the elasticity of intertemporal substitution is close to unity. According to Elbasha and Roe (1996), it is less than unity, so that the relation between environmental quality and growth would be positive in this model.

The effects of trade on the environment and welfare are ambiguous. They depend on the price elasticities of the supply of traded goods, on the terms of trade-effects on growth, and on the pollution intensities of the different sectors. Numerical exercises suggest that trade worsens the environmental quality but enhances welfare.

The added value of this model compared to static approach consists in including the dynamic dimension in the determination of welfare. Being able to treat, in a consistent framework, the effects of trade on the environment and on growth simultaneously, policymakers become better informed about the whole variety of consequences of different trade policy measures.

Whether an endogenously growing small open economy is able to implement an independent environmental policy crucially depends upon the tax system (see Hettich and Svane, 1998). Under a residence-based income tax, which discriminates between domestic-source and foreign-source income, it is possible to implement an independent environmental policy which has an impact on the domestic interest rate. The impact of a change in the interest rate can only be fully captured in a dynamic setting. While a static model will only provide information on the input mix at a certain point in time, a dynamic model is able to show the influence of the interest rate on intertemporal decisions determining the growth rate. By using a residence-based income tax, a country is thus able to determine its own growth rate. Under a source-based tax system, however, where the after-tax interest rate equals the world interest rate, the government can no longer implement its own first best environmental policy.

2.4.2 Comparative Advantage

Considering the supply of natural resources, labour, and capital in rich and poor countries, Anderson (1993) explains why exports of backward countries will first be concentrated in primary products. In a second stage of development, according to his contribution, the comparative advantage of lagging economies will gradually shift to manufactures and, eventually, to services. In this way, it is possible for later-industrialising countries to export their way out of poverty. This development process is, however, often hindered by government interference. Governments of poorer economies tend to discriminate against the primary sectors and in industrialised countries declining industries tend to be protected. In many cases, protectionist trade policy measures are claimed to address environmental problems (Schulze and Ursprung, 2001c). The agriculture and mining (coal) sectors are, however, policy fields in which good examples of trade liberalisation is liable to improve the state of the environment and, thereby, the basis for international sustainable development (see Anderson, 1993 and Ervin, 2001).

2.4.3 North/South-Relations

A different effect of environmental policy on R&D-driven growth, results if only certain countries are able to innovate, whereas others are not. This asymmetry underlies in the so-called dynamic "North/South"-models, which divide the world in a dynamic and innovative region, called "North", and a less developed region, called "South". Bretschger (1998b) analyses the effects of an environmental policy undertaken by the North on worldwide natural resource use which causes global pollution and on the growth rate of the world economy. To determine economic activities in the South, two versions of the displacement of production from the North to the South are considered. In the first version, the South imitates the product designs of the North ("imitation hypothesis"). In the second version, the North has the opportunity to shift the production to the South ("production shift hypothesis").

Rather surprisingly, the results obtained are very similar for the two versions. Under realistic parameter constellations, a decreasing pollution in the North (achieved by environmental policy) is not offset by an increasing pollution in the South. Even in cases where pollution in the South rises as a consequence of an increased economic activity in the South, the worldwide positive effect of Northern environmental policy on nature is still guaranteed. The growth effect of the decrease in pollution in the North is ambiguous. It is dependent on the flexibility of the production process, which is measured by the elasticity of substitution between natural resources and labour (being the other primary production input). If this elasticity is small, the worldwide growth rate increases. This is due to the cost effect in the dynamic sector and corresponds to the QIDI-models (see above). If this elasticity is large, worldwide growth decreases. According to the results of this model, the slowing-down of growth does not, in most cases, mean that the growth rate becomes negative. Furthermore, the analysis shows that the imitation effect, compared to the production shift effect, has a larger impact on the environment but a weaker one on growth. Worldwide sustainability is a very likely outcome under all possible scenarios. Thus, free trade among different world regions does not, in general, appear to endanger the goal of worldwide sustainability.

2.4.4 International Cooperation

It is obvious that international agreements on environmental standards have growth effects (see van der Ploeg and Ligthart, 1994). The non-cooperative outcome of a differential game for a global economy is characterised by an excessive use of (renewable) natural resources due to the apparent international environmental externalities. International policy cooperation results in a reduced use of resources, lower growth, increased welfare, and an improved environmental quality, unless there are positive international knowledge spillovers in production and/or international spillovers in public spending. However, the opposite result concerning environmental quality and growth cannot be excluded. If there are international knowledge spillovers in production and if public spending in one country benefits productivity in other countries as well, optimal international policy coordination can harm environmental quality and boost the economic growth rate. These results are derived under the assumptions that (i) the period of commitment is equal to the planning horizon, (ii) only two countries are involved in negotiating and (iii) the countries are identical. For a detailed discussion of these assumptions see Schmidt (2001).

2.4.5 Trade and Resource Growth

The impact of free trade on welfare in economies with open access renewable natural resources is analysed in Brander and Taylor (1997a and 1997b). The authors establish that the pattern of trade and the structure of production depend on a simple ratio of the biological resource and the country's labour endowment growth rate. Aside from the resource good, manufactures are consumed. For a broad range of parameter values, the resource exporting country will not fully specialise in producing the resource good. The steady-state utility levels fall in this country as a consequence of a move to free trade because the open access externalities are aggravated by trade, that is by an improvement in the terms of trade. While the intuitive link from low resource-management standards to increased resource exports and lower welfare can be portrayed in this model, the authors show that this link does not emerge under various conditions. If we assume that harvesting the resource becomes more difficult as the stock is depleted, productivity in harvesting rises with an increasing stock. A well-managed resource is then relatively cheap in the long run and a conservationist country may well be able to obtain a comparative advantage in the resource good. According to the authors, when introducing trade with a country that has a very poor resource management, the conservationist exports the resource good and both countries experience an increase in welfare. If, on the other hand, the non-conservationist country overuses its resource to a lesser extent, the result is reversed and the conservationist country is not compensated for its resource management but experiences a welfare loss, as does the non-conservationist country.

2.5 Empirical Evidence

Summarising the behaviour of the surveyed models, the impression of an ambiguous relation between the state of environment and economic growth emerges. The more complex models, which include elements such as different sectors, international trade, and abatement activities, suggests a negative relation between natural resource use and long-term growth. Under these circumstances it is paramount to look at the empirical relation between the income level and the state of the environment and, in addition, to compare the natural resource use and the growth performance of different countries.

2.5.1 Environmental Kuznets Curve

Looking at the correlation between per capita income and the pollution of the environment in an international comparison, pollution seems to follow a hump-shaped pattern, the so-called "environmental Kuznets curve" (see Grossman and Krueger, 1995 and Grossman, 1995). Structural changes in the composition of aggregate output, the replacement of old capital by new capital, and environmental policy are the most important reasons for decreasing pollution after a certain stage of development is reached (see McConnell, 1997). The inverted U-shaped pattern especially applies to certain regional pollution effects, such as urban air quality and water quality in rivers, where abatement is relatively inexpensive. However, it does not apply to global pollution effects such as greenhouse emissions, to commercial energy consumption or to municipal waste (see Moomaw and Unruh, 1997 and Rothman, 1998). In addition, it has been shown that highly developed countries have been able to reduce their energy requirements by importing manufactured goods which used to be produced in the domestic economy at earlier stages of development (see Suri and Chapman, 1998). So the observed improvements in environmental quality might therefore well be a consequence, at least in part, of the increased ability of consumers in wealthy nations to distance themselves from polluting production.

2.5.2 Natural Resources and Growth

As has become clear from the theoretical analysis, economies with abundant natural resources do not need to grow faster than countries with only few natural resources. Sachs and Warner (1995) show for the period 1971 - 1989 that economies with a high initial GDP share of natural resource exports tend to have low growth rates during the subsequent period. This negative relationship holds even after controlling for initial per capita income, trade policy, government efficiency and investment rates, which are all considered to be important in explaining the growth rate. The authors mention motivation problems of individuals who get rich easy, increased rent-seeking behaviour in resource-abundant economies and the decrease of the manufacturing sector as possible explanations for their findings. The last argument refers to the motivation underlying industrialisation policies in the 1940s and 50s and the discussion of the so-called "Dutch Disease". The special attributes of industrialisation are the high intensity of backward and forward linkages to the rest of the economy and the intensity of learning externalities, that is of positive spillovers. In some estimations, the authors find modest support for the Dutch Disease hypothesis.

Gylfason et al. (1999) investigate the dynamic implications of natural resources endowments on per capita growth by approximating the supply of natural resources with the size of the primary and secondary sector, in which primary goods (agriculture, fishing, forestry and mining) are produced by using an alternative technology. In a cross-section estimation with the explanatory variables initial GDP, initial share of the labour force employed in the primary sectors, external debt in proportion to GDP, real exchange rate volatility, initial primary and secondary school enrolments, and an Africa dummy, the authors find a statistically significant negative relationship between the size of the primary sector and the average rate of growth. The explanatory power of the eduction variable is reduced when primary sector employment or primary sector exports are used as additional explanatory variables. This seems to support the hypothesis that a preponderance of the primary sector production tends to inhibit economic growth by discouraging investments in human capital or research and development. However, the measure for natural resource supply is very broad in this study. Moreover, the measure does not discriminate between natural resource problems and the well-known structural problems of farming and mining.

2.6 Lessons and Open Issues

2.6.1 Some Lessons

In the public debate, economic growth, the globalisation of markets, and the increasing specialisation of regions or countries are often viewed as major threats to the sustainability of long-term development. The surveyed literature reveals, however, that this negative view is not appropriate. Growth and free trade provide a variety of options for solving the current environmental problems. To be sure, the existence of different options does not mean that present generations automatically choose a sustainable development path. It should also be remembered that environmental problems are the consequence of market failures which are already present in a static representation of the closed economy. These inefficiencies may well be aggravated by free trade and economic growth, which has to be taken into account when formulating appropriate policy measures. Finally, for sustainability, the requirement of fairness regarding future generations has to be added explicitly to the general policy guidelines.

Most contributions to the literature in the field of environment, growth, and trade focus on the first two aspects and thus neglect the international dimension. What lessons for sustainability can be learned from this limited approach, and what results can be generalised for the general topic of sustainability in open economies. The most important lesson from the combination of growth theory and environmental economics is that economic growth and environmental care are compatible in principle. This statement is valid independent of the observation that certain natural resources are over-used in the present situation. Pollution is due to market inefficiencies and the current use of exhaustible resources hardly satisfies intergenerational fairness considerations. To better preserve the natural capital stock, it is therefore necessary to reduce the use of certain natural resources. On the other hand, sustainability requires that welfare does not decrease in the future. The decreasing amount of natural inputs therefore needs to be sufficiently compensated for by the accumulation of man-made inputs consisting of different forms of capital. The greater the saving effort of the present generation is, the easier the substitution of natural resources in production and consumption becomes. But saving means consumption renunciation and this renunciation is economically attractive only if the proceeds from saving and investment are sufficiently high. An adjustment of the relative prices under the title "removal of external costs" is already advisable in the name of present-day environmental protection. However, with internalisation, we obtain optimal development paths but sustainability is not yet guaranteed. Even stronger measures and an additional acceleration of the substitution of natural resources in the production are necessary for future generations not to fall back to a lower utility level on optimal growth paths.

Traditional one-sector models conclude that conditions for the sustainability of long-term development are favourable, provided that the elasticity of substitution between the natural resource and accumulated capital is high. Moreover, the existence of substantial positive spillovers is shown to be advantageous for sustainable growth. These preconditions may well be disputed. It is for this reason that an additional mechanism has to be emphasised in this context. This mechanism, which is represented in multi-sector models only, is the continuous reallocation of resources between the different sectors of an economy. Learning-intensive sectors should increase their share of aggregate production while natural resource-intensive sectors should gradually shrink over the course of time. If one proceeds the realistic assumption that natural resource intensity and learning intensities are negatively correlated between the different economic sectors, intersectoral reallocation of resources becomes one of the most powerful instruments to achieve sustainability. In this way, sufficient new knowledge capital and human capital, which substitute for the natural resources in the long term, can be formed. New knowledge also allows one to realise a massive increase in efficiency when using natural resources.

The impact of trade on economic growth is determined by scale and resource reallocation effects. Analogous effects are working in the context of sustainable growth. The main difference is that economic growth often generates positive externalities while environmental problems generate negative externalities. Scale effects induced by international trade unambiguously support capital accumulation and thus the mechanics of economic growth. If the accumulation of capital harms the natural environment, it is necessary to tighten environmental policy according to the increased growth rate. On the other hand, it is possible that the additionally accumulated capital is a substitute for the use of natural resources, as is the case for human or knowledge capital. Then, a higher growth rate improves the conditions for sustainable development. One should note that the internalisation of the economy has, in the case of scale effects, only an indirect effect on the natural environment through the effect on growth. For the various resource reallocation effects caused by trade, the impact on the environment and sustainability is more direct. The positive aspect of internalisation is that the principle of comparative advantage in international trade may improve worldwide conditions for knowledge production and for abatement of environmental damage. As relative costs of these activities are not the same across countries, sustainability can be achieved at the lowest economic cost, by means of international labour division. On the negative side, there are cases where trade decreases the quality of the natural environment through the induced change in relative prices. As seen above, in small open economies and in the case of open-access renewable natural resource, this result can emerge under realistic scenarios. Nevertheless, in the case of renewable resources, if productivity positively depends on the natural capital, strong resource management rules increase a country's international competitiveness. Considering the global climate as a renewable natural resource, it becomes obvious that such a productivity incentive is not effective everywhere. For the greenhouse problem, the external costs are global but the effect of a single polluting country is small in comparison to the whole world. A comparable productivity mechanism cannot be assumed for non-renewable natural resources either, if the current use is found to be non-sustainable. The only way to decrease the worldwide use of these resources consists of international policy coordination (see Schmidt, 2001 and Congleton, 2001).

The lesson for environmental policy consists in the finding that appropriate tax instruments, usually summarised under the heading of "green tax reform", can improve the protection of the environment as well as produce additional economic growth. This double effect is made possible by a double market failure, consisting of negative environmental externalities and of positive externalities (such as positive knowledge spillovers) in the growth sectors. Of course, direct instruments for internalising the positive spillovers could be implemented as well. If this is the case, the growth stimulating effects of the green tax reform are radically diminished. If direct internalisation is not under-taken, possibly for political reasons, the indirect way of correcting the growth deficit by increasing costs in growth-extensive sectors is effective and efficient. In this way, the government can provide benefits to spillover-intensive sectors without having to favour specific sectors or specific research projects. Thus, the allocation of resources within the dynamic sectors remains the decision of the firms.[1]

One should also note here that even a globalised world does not require all sustainability policies to be implemented at the international level. If environmental externalities are purely local or regional in nature, free trade and economic growth cannot be used as arguments against environmental policy. Regional or local policy measures are efficient in open economies, if certain conditions are observed. For example, given the mobility of capital, the tax system needs to be especially designed in order to be effective. In particular, if capital taxes are to be used to reduce pollution via production (capital), a residence-based tax system is called for. Otherwise, the pollution tax has no effect on the environment.

The lesson emerging from the analysis of North/South-models is that the shift of production from the North to the South as a consequence of environmental policy in the North is minimal under reasonable assumptions. The reason is that the production shift itself is not free. Rather, it requires resources of the South if Northern products are copied; it even includes Northern resources, when production is actively relocated by Northern firms. In addition, every shift from North to South sets Northern resources free which can, for example, be used for additional knowledge production. The conclusion is that environmental policy needs to be adjusted to conditions pertaining to trade and growth. An appropriately adjusted environmental policy is still highly effective in bringing about sustainable development paths.

A different conclusion must be drawn for trade policy. Generally speaking, trade policy is not a good instrument to achieve global sustainable growth. Many existing restrictions on free trade, for example in agriculture and coal-

[1] On the "double dividend" issue, see Smulders (2001).

mining, are not in favour of sustainable development. Lowering the barriers between countries, by intensifying the forces of comparative advantage, decreases natural resource use and increases knowledge accumulation. In general, free trade enhances the substitution process of natural resources which is crucial to achieve sustainability. The reason that trade is blamed for certain problems regarding the long-term development is that trade can, under certain conditions, amplify problems that are already present in autarky. It is obvious that an adequate solution to these homemade problems serves to obtain both the benefits of a better environment as well as the gains from trade.

An important related issue is the promotion of international knowledge diffusion. The non-rivalry property of knowledge and the massive progress in communication technologies represent favourable preconditions for a successful international transmission of knowledge and thus for promoting worldwide growth. International policy coordination is appropriate whenever externalities cross national borders or the exhaustion of natural resources has worldwide consequences. Global environmental problems like the greenhouse effect require global policy coordination. Especially in the case of rain forest protection (Barbier, 2001) and the protection of specific species (biodiversity), the losers from preservation should be compensated. Knowledge and capital transfers to poorer countries which are abundant in the supply of these natural resource are also good development policy instruments. If knowledge transfers are effective, Third World countries are in a better position to realise sustainable development paths.

2.6.2 Issues Remaining for Research

Sustainability is not only a worldwide political objective, environmental quality and economic growth are also both largely influenced by the economic relations between economies and world regions. We are thus led to conclude that combining elements of growth theory, international trade, and environmental economies represents a very promising field for further economic research. Many existing results of growth theory are only valid for closed economies. For open economies, one should try to confirm, reject, or refine the existing results. In any case, whether working with models of closed or open economies, in the future more effort should be spent on investigation which kinds of capital, under which circumstances, substitute for natural resources. Only with a solid grasp of this substitution process can we ever hope to obtain appropriate results for open economies in particular. The instances in which economic growth and environmental protection complement each other should be better identified by further research. Whenever pollution diminishes the productivity in the dynamic sectors, such as education and research, abatement measures reduce pollution and promote growth at the same time, which is an especially favourable constellation to implement environmental policy.

The findings applying to small open economies need to be generalised to capture large open economies with flexible prices and wages. It would be of great advantage to have a generally accepted model for international sustainability analogues to the traditional 2 x 2 x 2 trade model. Such a framework could intensify and focus the discussion on certain crucial topics which proved to be very productive in other strands of economic theory. The different forms and impact of international knowhow transfers also require more careful study in the future. Moreover, a more subtle analysis of the implementation of environmental policy should be a focus of further research. For example, the joint implementation of environmental policies in the international community seems to be one of the most efficient ways to obtain worldwide sustainable development. To be successful in this area, the dynamic consequences of such agreements should be better understood.

A further issue is the treatment of risk. Since information on the impact of economic activities on the ecosystem is incomplete, the methods of decision-taking under uncertainty should be better integrated in the theory of sustainable growth in open economies. For example, uncertainty and irreversibility may provide guidelines for the substitution of natural resources which greatly differ from the ones obtained under complete information. This applies especially to the sustainability objective of intergenerational fairness whose policy implications crucially depend on the available information with respect to the long-term development prospects.

Therefore, economic theory should aim at improving our understanding of the future consequences of environmental policies today.

Chapter 3

Economic Growth and the Diffusion of Clean Technologies: Explaining Environmental Kuznets Curves*

Production often causes pollution as a by-product. Once environmental degradation becomes too severe, regulation is introduced by which society forces the economy to make a transition to cleaner production processes. We model this transition as a change in "general purpose technology" and investigate how it interferes with economic growth driven by quality-improvements. The model gives an explanation for the inverted U-shaped pollution-income relation found in empirical research for many pollutants (Environmental Kuznets Curve). We provide an analytical foundation for the claim that the rise and decline of pollution can be explained by policy-induced technology shifts and intrasectoral changes.

* This chapter represents joint work together with Sjak Smulders (Tilburg University) and Lucas Bretschger (ETH Zurich).

3.1 Introduction

An old, classical and recurring theme in economics is the relationship between economic growth and concern for environmental problems. It ranges from the physiocrats' focus on land, Jevons's coal question and the Club of Rome's doomsday scenarios, to the current greenhouse gas problem. The Environmental Kuznets Curve (EKC) is one of the most-used concepts to analyse the pollution-income relation and has recently attracted considerable attention. Empirical EKC studies find evidence for an inverted U-shaped pollution-income relation for many pollutants, in particular for short-lived air and water pollutants that have local and immediate effects.[1] The theoretical EKC literature explains the hump-shaped pollution-income relation from, among others, scale economies, income-induced policy changes and exogenous shifts in the nature of growth.

In the paper at hand, we study the relationship between endogenous economic growth and pollution in a model in which pollution problems first gradually build up with the introduction of new technologies, new materials and new energy sources. Environmental degradation attracts the public's attention and triggers a regulatory response in the form of a pollution tax. Finally, firms adopt cleaner technologies to minimise costs. We use the model, first, to give an integrated explanation for the EKC, second, to analyse how technological change may drive pollution reductions when the economy grows and, third, to show how intrasectoral – rather than intersectoral – shifts accompany the adoption of pollution-reducing technologies.

We differ from the existing theoretical literature on the EKC since we treat changes in technology as endogenous. In particular, innovation opportunities and incentives not only determine the growth rate of income, but also

[1] For example sulphur dioxide, nitrogen oxides or suspended particulate matter. For a survey of the empirical evidence see e.g. the special issues of *Environment and Development Economics* 1997 and *Ecological Economics* 1998, or the recent review articles by Stern (2004) and Lieb (2003).

whether technological change is pollution-using or pollution-saving. Usually, the theoretical EKC literature assumes either exogenous income (Lieb, 2002; Andreoni and Levinson, 2001), exogenously given factor endowments that determine income (Copeland and Taylor, 2003 chapter 3) or exogenous technological change (Brock and Taylor, 2004). Previous results, however, have pointed out that the source of growth and the nature of technology determines whether economic growth and pollution are linked or delinked. What is missing in the theoretical EKC literature is an explanation of why and how the sources of growth change and how they are related to pollution problems. To make both income and technology endogenous, we use a Schumpeterian endogenous growth model. Other endogenous growth models have studied the link between income and pollution, but have neglected temporal shifts in the direction of technological change as resulting from profit incentives.[2] For example, Stokey (1998) generates the EKC in a model with exogenous technology. Aghion and Howitt (1998) have extended her model by introducing endogenous technology, but focus on balanced growth only and do not distinguish between pollution-using and pollution-saving technological change. Finally, de Groot (1999) models an EKC with technological change as a learning-by-doing process.

Besides the shifts towards cleaner production technologies a second mechanism is often stressed in explaining the decoupling of environmental degradation from economic growth: changes in the composition of production.[3] Shifts between agriculture, manufacturing and services as well as intersectoral shifts within manufacturing have been relatively small in recent decades in developed countries, see Torvanger (1991) and de Bruyn (1997). An exception is the US, where dramatic shifts towards cleaner industries have been observed at the end of the last century (Ederington et al., 2004). Hence,

[2]See Smulders (1995a, 2000) for surveys on environmental growth models and Bretschger (1999) for the integration of natural resource use into modern growth theory.

[3]See Copeland and Taylor (1994) for the distinction between scale, composition and technique effects.

such composition effects can account for at most a small part of the EKC. But, there is strong evidence for the importance of intrasectoral change. For example, Jänicke et al. (1997) report that in 1989 the industrial final energy consumption of Germany was 30.4% lower than it would have been without intrasectoral change since 1970. The corresponding figures for Japan and Sweden are 58.6% and 27.6%.[4] Moreover, in empirical decomposition analyses, intrasectoral changes are mostly subsumed under the label "technique effect", which usually accounts for the major part of emission reductions. This effect, however, contains more than purely technological changes. It also incorporates changes in the spectrum of goods produced in a sector, i.e. intrasectoral shifts, as well as substitution of inputs and the application of end-of-pipe technologies, see de Bruyn (2000).

While the literature has often used a decomposition of changes in pollution in terms of a scale, technology and composition effect, this decomposition has been purely descriptive, or as a decomposition of the effects of a shock (notably trade liberalisation shocks, see Copeland and Taylor, 2004). What is missing is an explanation of how and why the interaction of the composition, scale and technology effects can generate the EKC pattern. Our contribution to the theoretical literature on the EKC is an attempt to provide elements of these missing links. In particular, first we model how incentives arise to invest in pollution-intensive technologies before incentives become in favour of pollution-saving technologies, and, second, we sort out how over the technology lifecycle the balance between (intrasectoral) composition and technique effects changes so that the EKC arises. To do so, we carefully analyse firm behaviour under the different technology conditions.

The remainder of the paper is organised as follows. Section 3.2 provides an informal overview of the model and presents the general mechanisms producing EKCs. In Section 3.3, the formal model is introduced. The development of innovation and pollution in four different phases are analysed in Section

[4]By contrast, intersectoral change reduced energy consumption by only 13% in Germany and Japan and by 2.1% in Sweden.

3.4. In Section 3.5, it is examined to what extend the model accounts for empirical observations. Finally, Section 3.6 summarises and concludes.

3.2 An Informal Overview of the Model

This section gives an informal overview of the model. In particular, we describe how technology changes, how firms determine investments in new technologies and how pollution evolves over time. Because it aims to give intuitive information about the behaviour of the fairly complex model, this section does not strictly separate between assumptions, derivations and results. This will be done in the subsequent sections.

Technology changes along two dimensions. First, firms improve the quality of their products incrementally. Second, pollution-saving and pollution-using inventions arise in clusters at discrete times. They can be interpreted as *general purpose technologies* (GPT), defined by Bresnahan and Trajtenberg (1995) as technologies that have a potential to affect a large part of the economy. For example, we can think of energy systems: the use of horsepower, fossil fuels or nuclear power as source of energy constitute milestones in energy production. Such technology changes had and have a large impact on pollution, e.g. in the context of the regional pollution of air and water.[5]

Both types of innovation, i.e. quality improvements and the adoption of a new GPT, are costly and require R&D expenditures. Firms choose the type of innovation that yields highest profits. Since it is costly to adopt new technologies, diffusion is slow and producers using old technologies may coexist with producers using new ones. Thus, firms are heterogeneous in terms of pollution output ratios, prices and output levels. Changes in pollution result not only from changes in the scale of activity and the technique used within

[5]GPTs have been studied in endogenous growth literature in the context of Romer's variety expanding model (Helpman and Trajtenberg, 1998) or models of growth based on inhouse R&D (Nahuis, 2003). We contribute to this literature by modelling GPTs in the quality ladder framework (Grossman and Helpman, 1991 chapter 4).

firms, but also from the process of creative destruction in which producers of one type are gradually replaced by producers of another type.

As our model has to include several technologies, different types of producers and different types of product qualities, the framework runs the risk of becoming very complex. To reduce complexity, we make two simplifying assumptions. First, we set up the model such that only one type of innovation is being undertaken at a certain moment in time, either quality improvements or new GPT adoption. Second, at most two types of firms are active at any point in time. That is, after the occurrence of an new GPT no quality improvements are undertaken until all sectors have adopted the new GPT.

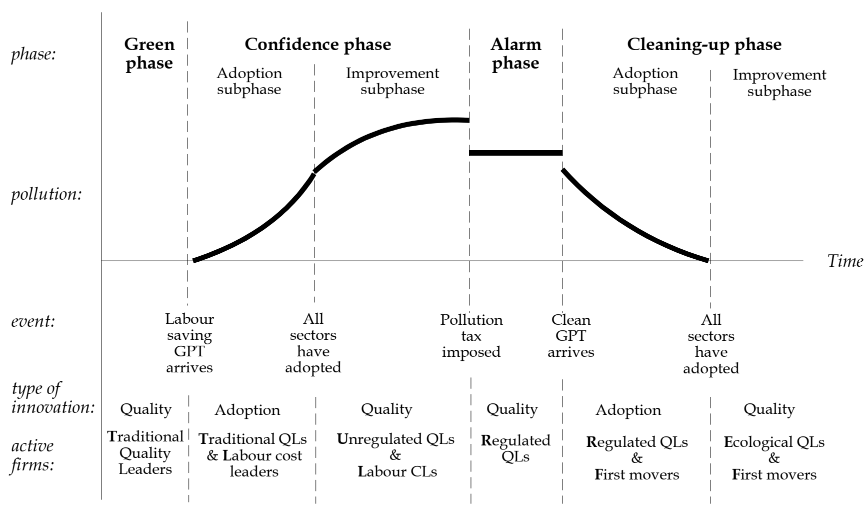


Figure 3.1: Overview of the model

In the model, we distinguish four phases, of which the main characteristics are summarised in Figure 3.1. In the first phase, the so-called "green phase", only one GPT is available, which causes no pollution. In the second phase, a new GPT becomes available and is gradually adopted; this defines the "adoption subphase". Firms invest in the adoption of the new GPT since it saves on their labour costs. Once all sectors in the economy have adopted the new GPT, firms again invest in product quality improvements; this defines the "improvement subphase". Yet, to operate the new GPT, pollution cannot be avoided. As a result, pollution rises, first, with adoption and, subsequently, with rising output. The latter is due to the fact that firms, which have improved their product quality, charge a lower price and produce more than their predecessors. However, pollution is not yet recognised as a problem. Accordingly, we call the second phase the "confidence phase". The third phase starts once it becomes clear that the new technology is harmful and once public concern has become widespread. Correspondingly, the third phase is labelled "alarm phase". The government responds to the public's concern by taxing emissions. As a result, firms cut back production and pollution decreases. As soon as a new, clean GPT becomes available, a new phase of adoption starts. We assume that this third GPT allows firms to reduce costs since it saves on pollution tax expenditures. With its invention, the "cleaning-up phase" starts. The clean GPT is gradually introduced in the different sectors of the economy and pollution decreases in the course of time (during the adoption subphase). Ultimately, all firms have adopted the new, clean GPT and, therefore, pollution is absent and firms again invest to improve their product quality (improvement subphase).

Over time, technological change not only affects the level of pollution, but also market structure. Firms that improve quality drive producers with lower quality levels out of the market. Similarly, firms that adopt a new GPT drive producers exploiting the old technology out of the market. The bottom part of Figure 3.1 indicates the different types of firms that are active in each phase. In the green phase, all incumbent firms use and improve the first GPT; we refer to "traditional quality leaders". The next GPT entails lower labour costs. Hence, firms that have adopted this GPT are called "labour-cost leaders" and gradually replace traditional firms. As soon as all traditional firms are replaced by labour-cost leaders, researchers start inventing blueprints to upgrade goods qualities. Firms buying these blueprints replace in turn the initial cost leaders. As there is no environmental regulation, we call this firms "unregulated quality leaders". In the alarm phase, unregulated quality leaders suddenly become "regulated quality leaders" as they are now taxed for their emissions. Once a new clean GPT has arrived, firms that have adopted this GPT enter the market and replace regulated quality leaders. We call these firms “first movers”. Once all sectors have switched to the clean technology, sectors start investing in quality upgrading. As a consequence, “ecological quality leaders” gradually penetrate the market.

3.3 The Model

There is a continuum of sectors, indexed i, each producing a good that enters the households’ utility function as an imperfect substitute. Each good can be produced in a number of varieties. Varieties differ in two dimensions. First, different qualities, indexed m, of the same good can be produced. A new generation of the product is of higher quality. Second, the labour input requirements and pollution output ratios for a given quality level may differ according to the general technology, indexed j, used.

Pollution hurts households’ utility. Whether a new technology causes pollution or not is unknown at the time of its introduction. Only when exposure to the pollutant has been long enough, damages, if any, can be established and an emission tax is implemented. This increase in production costs makes it attractive to switch to new production processes with lower pollution output ratios.

Households

The representative consumer maximises intertemporal utility given by:[6]

$$U_0 = \int_0^{\infty} [\ln (C_t) - Q_t] e^{-\rho t} dt \tag{3.1}$$

where ρ is the utility discount rate, C is the index of consumption, Q is harm from emissions, which consumers take as given, and t is a time index.

[6] Households are modelled exactly as in Grossman and Helpman (1991), but for the inclusion of damages in the utility function.

Consumers have Cobb Douglas preferences over a continuum of goods indexed i on the unit interval. Differentiated products of a given good i substitute perfectly for one another, once the appropriate adjustment is made for quality differences:

$$\ln(C_t) = \int_0^1 \ln\left(\sum_m q_{im} x_{imt}\right) di \tag{3.2}$$

where q_{im} is the quality of the mth product generation in sector i and x_{imt} is the associated production at time t. Maximisation of utility subject to the usual budget constraints implies that only the good with the lowest price per unit of quality is consumed in each sector i. We denote this good by $\tilde{m}_i$. Static utility maximisation implies:

$$\begin{aligned} x_{imt} &= Y_t/p_{imt} \quad \text{for} \quad m = \tilde{m}_i \\ x_{imt} &= 0 \qquad\qquad \text{otherwise} \end{aligned} \tag{3.3}$$

where $Y_t \equiv \int_0^1 \left(\sum_m p_{imt} x_{imt}\right) di$ denotes total consumption expenditure and p_{imt} is the price of good i of quality m at time t.

Utility maximisation also implies that consumption expenditure Y grows at a rate equal to the difference between the (nominal) interest rate r and the utility discount rate:

$$\dot{Y}/Y = r - \rho. \tag{3.4}$$

Production

Each producer holds a unique blueprint (patent) for production such that the market form is monopolistic competition. The blueprint allows the holder to produce good i at quality m, using technology j.

Unit production costs vary with technology but not with sector or quality. Production of one unit of output x requires a_{Lj} units of labour and emits a_{Zj} units of pollution if technology j is used. Unit costs c for technology j at time t are thus given by:

$$c_{jt} = a_{Lj} w_t + a_{Zj} \tau_t \tag{3.5}$$

where w and τ denote the wage and pollution tax respectively. Output in each sector is given by:

$$x_i = Y/p_i, \tag{3.6}$$

that is spending per sector, Y (which equals aggregate spending because the total mass of sectors is normalised to one), divided by the price set by the incumbent in the sector, p_i.

Within a sector, firms engage in Bertrand competition.[7] The leading firm sets the limit price that equals the cost level of its closest rival corrected for quality differences. It is useful to distinguish between two (broad) types of firms: cost leaders and quality leaders. Cost leaders are the first producers in the sector that have introduced a new general purpose technology. They have a cost advantage over their closest rival (but produce the same quality level). Cost leaders using technology j set a price equal to their rival's cost level c_{j-1}. Quality leaders are the producers that supply the highest quality level in the sector. They have a cost advantage over their closest rival in terms of costs corrected for the quality lead (but use the same technology). A quality leader using technology j sets the limit price λc_j, where $\lambda > 1$ represents the quality difference. Since new blueprints for higher quality levels become available as a result of the innovation process (with the newest quality level being λ times the previous quality level developed), quality leaders are always

[7] The assumption of Bertrand competition among equal-cost producers of perfect substitutes results in marginal-cost pricing and zero operating profits. These strong results are debatable and not in line with costly R&D. However, the presence of product differentiation softens the strongly competitive results of the pure Bertrand competition and results in - as with Cournot competition - prices above marginal costs and positive operating profits. This, however, does not compulsorily mean that the presented results hold true for other assumptions regarding the market structure.

λ ahead. This implies that we may write for the price set in sector i:

$$\begin{aligned} p_i &= \lambda c_j && \text{if in } i \text{ a quality leader is active that employs technology} j \\ p_i &= c_{j-1} && \text{if in } i \text{ a cost leader is active that employs technology} j. \end{aligned} \tag{3.7}$$

Corresponding profit levels are then given by:

$$\begin{aligned} \pi_i &= \left(1 - \tfrac{1}{\lambda}\right) Y && \text{if in } i \text{ a quality leader is active,} \\ \pi_i &= \left(1 - \frac{c_j}{c_{j-1}}\right) Y && \text{if in } i \text{ a cost leader is active that employs technology} j. \end{aligned} \tag{3.8}$$

Let us now be more specific and distinguish between the three GPTs and six types of producers already described above. The three GPTs appearing in the model are indexed $j = 1, 2, 3$ for the "traditional", "labour-saving" and "clean" technology respectively. GPT 1 requires one unit of labour per unit of output and emissions are zero. GPT 2 requires $\eta < 1$ units of labour, but emits one unit of the pollutant per unit of output. GPT 3 is again a zero-emissions technology and requires γ units of labour per unit of output. We assume that GPT 3 improves upon GPT 1, i.e. $\gamma < 1$. Hence we may write:

$$a_{L1} = 1, a_{L2} = \eta < 1, a_{L3} = \gamma < 1, a_{Z1} = a_{Z3} = 0, a_{Z2} = 1. \tag{3.9}$$

In the green phase and in the confidence phase, there is no tax on pollution, that is $\tau = 0$, but from the alarm phase onward, emissions are taxed. The tax is assumed to be constant in terms of the wage, and we then have $\tau/w > 0$.

The six types of producers described in Section 3.2 and the bottom part of Figure 3.1 are index by $k \in \{T, L, U, R, F, E\}$, where T denotes "traditional quality leaders", L "labour cost leaders", U "unregulated quality leaders", R "regulated quality leaders", F "first movers" and E "ecological quality leaders".

Using equations (3.7) and (3.8) it is now straightforward to determine prices and profits of each type of producer. Table 3.1 gives the results for producers of type k.

Table 3.1: Prices and profits for the six types of producers

k	T	L	U	R	F	E
p_k	λw	w	$\lambda\eta w$	$\lambda(\eta w+\tau)$	$\eta w+\tau$	$\lambda\gamma w$
π_k	$\left(1-\frac{1}{\lambda}\right)Y$	$(1-\eta)\,Y$	$\left(1-\frac{1}{\lambda}\right)Y$	$\left(1-\frac{1}{\lambda}\right)Y$	$\left(1-\frac{\gamma}{\eta+\tau/w}\right)Y$	$\left(1-\frac{1}{\lambda}\right)Y$

Total employment in manufacturing, denoted by L_x, can be written as:

$$\begin{aligned} L_x &= n_T\frac{Y}{\lambda w}+n_L\frac{Y}{w}\eta+n_U\frac{Y}{\lambda\eta w}\eta+n_R\frac{Y}{\lambda(\eta w+\tau)}\eta+n_F\frac{Y}{\eta w+\tau}\gamma \\ &\quad +n_E\frac{Y}{\lambda\gamma w}\gamma \end{aligned} \tag{3.10}$$

where n_k is the number of sectors with firms of type k.

Total emissions are given by the sum of emissions of labour cost leaders, unregulated quality leaders, and regulated quality leaders. Hence, aggregate pollution Z can be calculated as:

$$Z = n_L\frac{Y}{w}+n_U\frac{Y}{\lambda\eta w}+n_R\frac{Y}{\lambda(\eta w+\tau)} \tag{3.11}$$

Innovation

R&D aims at developing blueprints for improving the quality of a certain product or blueprints for adopting the latest technology in a certain sector. The development of a blueprint requires a units of labour, so that the cost of a blueprint is aw. There are six types of blueprints corresponding to the six firm types. For example, there are blueprints for higher quality using the traditional technology (denoted by T) or blueprints for adopting the labour-saving GPT 2, denoted by L. We denote these blueprints as type $k \in \{T, L, U, R, F, E\}$. The total amount of blueprints developed per period, or the research intensity ι, is:[8]

$$\iota = \frac{1}{a}\sum_k L_{gk}, \tag{3.12}$$

[8] Since the number of sectors is normalised to one, the number of blueprints developed equals the fraction of sectors in which innovation occurs.

where L_{gk} is the amount of labour engaged in developing blueprints of type k.

The value of a blueprint equals the stock market value of a firm that exploits the blueprint. Free entry in research guarantees that, whenever research activity is targeted at developing blueprints of type k, the value of a firm of type k, i.e. v_k, equals the cost of the blueprint:

$$v_k \leq aw \qquad \text{with equality whenever } L_{gk} > 0. \tag{3.13}$$

The value of a firm is determined by the no arbitrage equation which states that the expected rate of return on stock must equal the return in an equal size investment in a riskless bond:

$$\pi_k + \dot{v}_k - s_k = r v_k \tag{3.14}$$

where s_k is the expected value of the capital loss that occurs because of shocks – technological innovation – to the sector. This capital loss crucially depends on what type of innovation is going on in the economy: whether it is quality improvement or adoption and which sectors innovation is aimed at. To solve the model, we only need to know the risk term for the type of firm for which new blueprints are developed. In the present model setup, only one type of blueprints is developed at a certain point in time. Whenever quality improvements are developed, quality leaders face the risk of being replaced by a new quality leader. They lose total value of the firm with a probability equal to the number of blueprints being developed; hence, $s_k = \iota v_k$. However, when researchers develop blueprints to adopt the newest technology, cost leaders – firms that already have adopted the new technology – face no risk until all firms have adopted the new GPT, such that $s_k = 0$.

Labour market

Labour is supplied inelastically and equals L. Labour demand consists of employment in manufacturing and total employment in R&D. Clearing of the labour market requires:

$$L = L_x + \sum_k L_{gk} \tag{3.15}$$

Compilation

To round off the formal presentation of the model, Table 3.2 summarises all variables of the model and the equilibrium conditions of the R&D sector, and the capital, labour and goods markets.

Table 3.2: Variables and equilibrium conditions

Exogenous Variables			
a	labour input requirement in R&D	η	labour input requirement of GPT 2
a_{Lj}	labour input requirement of GPT j	λ	quality difference
a_{Zj}	pollution intensity of GPT j	ρ	time preference rate
L	labour supply	τ/w	pollution tax in terms of wage
γ	labour input requirement of GPT 3		
Endogenous Variables			
C	consumption	U	utility
c	unit production costs	v	value of a firm
L_g	employment in R&D	w	wage
L_x	employment in manufacturing	X	total output
m	product generation	x	production of a good
n_k	numbers of sectors with firms of type k	Y	total consumption expenditures
		y	spending per wage income
p	price of goods	Z	aggregate pollution
Q	harm from emissions	ι	research intensity
q	quality of goods	π	profit
r	interest rate	τ	pollution tax
s	expected value of capital loss		
Equilibrium conditions			
$v_k \leq aw$	equilibrium in R&D		
$L = L_x + \sum_k L_{gk}$	labour market clearing		
$\pi_k + \dot{v}_k - s_k = rv_k$	no-arbitrage condition		
$x^S = x^D$	goods market equilibrium		

3.4 Innovation and Pollution in Four Stages

We now discuss the different stages of growth that the economy goes through. Each stage can be characterised by a state variable, which is the number of firms of one particular type. This number is inherited from the previous stage and endogenously changes over time in each stage.

3.4.1 Innovation and Pollution in the Green Phase

In the first phase, the green phase, all active enterprises are traditional firms, i.e. quality leaders using GPT 1. Innovation is exclusively aimed at improving product qualities. This reduces the model to the Grossman/Helpman model (1991, chapter 4). Since the clean GPT is used, there is no pollution at all. The rate of innovation is given below in equation (3.29).

3.4.2 Innovation and Pollution in the Confidence Phase

General equilibrium dynamics

In the adoption subphase GPT 2 is available for adoption, but has not yet been implemented in all sectors. Since adoption is costly, i.e. a sector-specific blueprint must be developed, it takes place only if the returns to this research investment are large enough. If research were targeted not only at adoption but also at quality improvement in traditional sectors, we would require $\pi_L = \pi_T$ for this to be an equilibrium, which only happens by coincidence. If $\pi_L < \pi_T$, no adoption would take place ($L_{gL} = 0$), the confidence phase would not start and the economy would remain in the green phase. Therefore, we focus on the more interesting case in which $\pi_L > \pi_T$ so that adoption takes place without simultaneous quality improvements in traditional sectors. Accordingly, we assume:

$$\eta < 1/\lambda. \tag{3.16}$$

Hence, once the new GPT becomes available, in the beginning all labour in R&D develops blueprints for adoption so that $L_{gk} = 0$ for all $k \neq L$, $a\iota = L_{gL}$, and $L_{gL} + L_x = L$. The relevant state variable in this phase is the number of labour-cost leaders n_L, which starts at zero. It increases with the number of patents developed:

$$\dot{n}_L = \iota = \frac{1}{a}\left(L - L_x\right) \tag{3.17}$$

As noted above, with adoption only, cost leaders face no risk of being replaced, i.e. $s_L = 0$. Using equations (3.8), (3.13) and (3.14), we find the following no-arbitrage equation for adoption:

$$\left(1 - \frac{c_j}{c_{j-1}}\right)\frac{Y}{aw} + \frac{\dot{w}}{w} = r \tag{3.18}$$

Substituting (3.4) into (3.18) to eliminate r, substituting (3.10) into (3.17) to eliminate L_x and taking into account $c_j/c_{j-1} = \eta$, $n_T + n_L = 1$ and $n_U = n_R = n_F = n_E = 0$, we find:

$$\frac{\dot{y}}{y} = (1 - \eta)\left(\frac{1}{a}\right)y - \rho \tag{3.19}$$

$$\dot{n}_L = \frac{L}{a} - y\left(\frac{1}{a}\right)\left(\frac{1}{\lambda} - \mu n_L\right) \tag{3.20}$$

where $\mu = (1/\lambda) - \eta > 0$ and $y = Y/w$. Note that y is not per capita income but spending per wage income. This system of differential equations in n_L and y characterises the dynamics of the first period of the confidence phase. The resulting phase diagram is depicted in Figure 3.2 by the $\iota = \dot{n}_L = 0$ locus, the lower d$y = 0$ locus and the curved path to the North East. The area above the $\iota = 0$ locus is infeasible since it represents negative employment in R&D. For any point below this locus, innovation takes place, causing the number of quality leaders n_L to increase. The area to the right of the line $n_L = 1$ is also infeasible since n_L represents a fraction of sectors, which cannot exceed unity. Adoption comes necessarily to an end if all sectors have adopted the new GPT. It is clear from (3.19) and (3.20) that this will happen in finite time. In the diagram, it happens when the $n_L = 1$ line or the $\iota = 0$ locus is hit. What exactly happens depends on the value y initially takes at the time that GPT 2 becomes available. At this time, the confidence phase starts at $n_L = 0$. Variable y has to jump initially such that the boundary conditions are satisfied. Since consumption is proportional to L_x and L_x is proportional to y [see (3.10)], consumption smoothing by households rules out a jump in y in the absence of unexpected shocks. Hence, the end condition for y in the adoption subphase is given by the initial value for y in the subsequent improvement subphase, which is determined below.

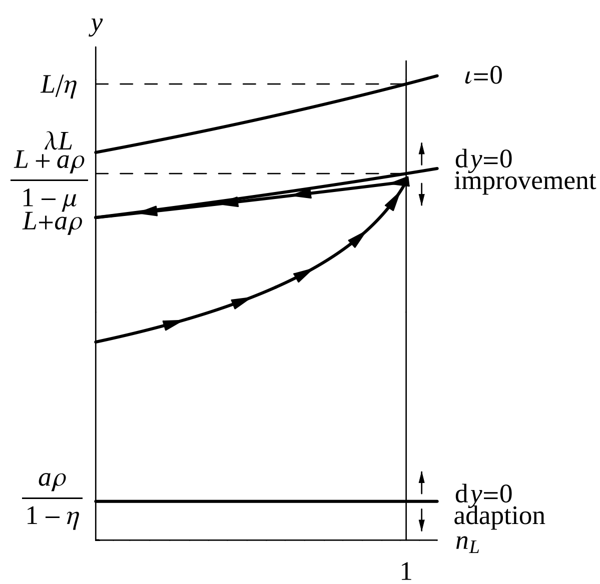


Figure 3.2: Dynamics confidence phase in the n_L, y plane

In the second period of the confidence phase, the improvement subphase, all sectors have switched to the new GPT. As there is no further possibility to invent blueprints for adoption and because research is still economically attractive, inventions are now directed at improving product qualities so that $L_{gk} = 0$ for all $k \neq U$ and $L_{gU} + L_x = L$. The rate of innovation can be again expressed as:

$$\iota = \frac{1}{a}(L - L_x) \tag{3.21}$$

The rate of innovation now reflects the fraction of sectors in which a new quality leader replaces an incumbent. Since an innovator is indifferent between replacing a quality leader (firm of type U) or a cost leader (L-firm) – in both cases, profits equal $(1-1/\lambda)Y$ – she spreads innovation effort equally over all sectors. As a result, a fraction n_L of the total number blueprints developed (ι) hits L-firms, which are then replaced by quality leaders. Hence we have:

$$\dot{n}_L = -n_L \iota \tag{3.22}$$

At the same time, ι is the probability for an individual quality leader that he will be replaced and will experience a complete capital loss. Hence, we have $s_U = \iota v_U$. Using (3.8), (3.13) and (3.14), we find the following no-arbitrage equation for quality improvements:

$$\left(1-\frac{1}{\lambda}\right)\frac{Y}{aw} + \frac{\dot{w}}{w} - \iota = r \tag{3.23}$$

Substituting (3.4) into (3.23) to eliminate r, substituting (3.10) into (3.21) to eliminate L_x and taking into account $n_L + n_U = 1$, $n_T = n_R = n_F = n_E = 0$, we find:

$$\frac{\dot{y}}{y} = (1-\mu n_L)\left(\frac{1}{a}\right)y - \left(\frac{L}{a}+\rho\right) \tag{3.24}$$

$$\frac{\dot{n}_L}{n_L} = \left(\frac{1}{\lambda}-\mu n_L\right)\left(\frac{1}{a}\right)y - \frac{L}{a} \tag{3.25}$$

This dynamic system in the n_L, y plane characterises the second period of the confidence phase. It is saddlepoint stable. Hence, starting at $n_L = 1$, y jumps to the saddlepath and asymptotically converges to $n_L = 0$ and $y = L + a\rho$. The path to the South West in Figure 3.2 depicts the dynamic adjustment. As a result of the determination of the starting- and endpoint of the improvement subphase, also the starting-point of the adoption subphase can be identified.

Pollution and innovation

During the confidence phase, untaxed emissions rise. This rise in pollution can be decomposed in a scale effect, technique effect and composition effect.

In the adoption subphase, pollution can be derived from (3.11) as:

$$Z = n_L y \tag{3.26}$$

Since both n_L and y gradually increase during the adoption subphase, we see immediately from (3.26) that the same holds for pollution. We argue that this happens because changes in scale, composition and technique all tend to increase pollution. First, the technique effect is positive, i.e. pollution enhancing, since GPT 2 is polluting. Second, when a sector adopts the new GPT, it not only starts to pollute but also reduces prices and produces more. The gradual adoption of the new GPT (n_L rises) changes the composition of total output. This corresponds to intrasectoral changes from clean to dirty firms. Finally, total production affects pollution. Defining total production as the sum of sectoral production levels, we find the following expression for the confidence adoption subphase [from (3.6) and Table 3.1]:

$$X \equiv \sum_k n_k x_k = y \left[\frac{1}{\lambda} + \left(1 - \frac{1}{\lambda} \right) n_L \right] \tag{3.27}$$

Because n_L and y gradually increase during the adoption subphase, we see immediately from (3.27) that total production gradually rises, so that the scale effect also contributes to rising pollution levels.

To describe the development of the innovation rate, we need to determine how L_x changes over time [see (3.17)]. The appendix (Section 3.7.1) shows that L_x increases (decreases) and innovation falls (rises) over time if η is large (small). The intuition is as follows. On the one hand, the rate of innovation tends to fall over time. This reflects the fact that the more sectors have switched, the fewer opportunities are left for further adoption and the sooner innovation has to be redirected to quality improvements, which yields a lower rate of return. Forward-looking behaviour of investors ensures that the rate of return is smoothed and research efforts are gradually reduced. With lower research efforts, labour becomes available to expand the scale of production. On the other hand, if production with the new GPT saves a lot of labour, i.e. if η is small, the opposite happens and labour becomes available for research. With a small η, the process of adoption is relatively fast and the scale of production as measured by L_x declines. Nevertheless, pollution increases over time since fast adoption allows the technique and composition effect to dominate the (pollution-saving) scale effect. The rise in pollution and the decreasing innovation rate (for a sufficient high η) during the confidence adoption subphase is illustrated in Figure 3.3 by the curve segments from $n_L = 0$ to $n_L = 1$.

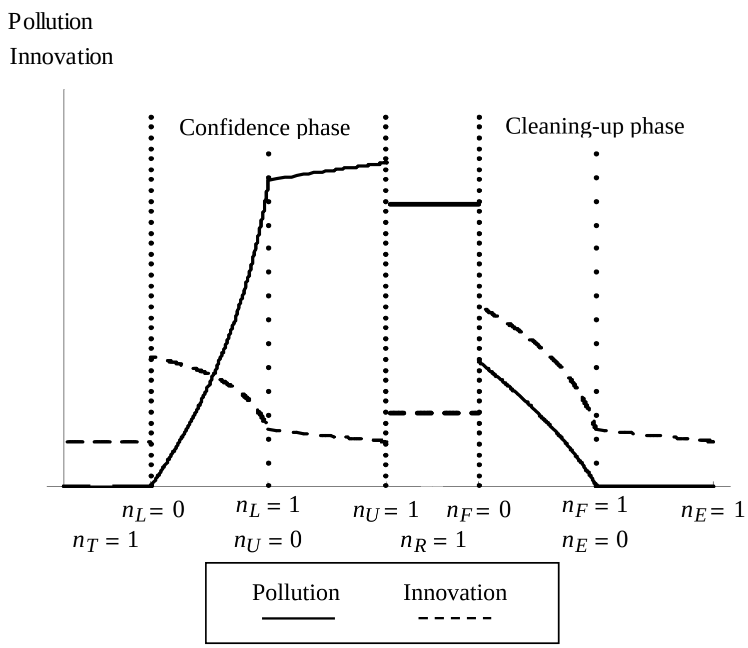


Figure 3.3: Pollution and innovation in all phases

In the improvement subphase, pollution increases as well over time, although at a decreasing pace. Since all sectors are using GPT 2 with a fixed emission output ratio, changes in pollution can be explained entirely by changes in total output (X) or labour in production (L_x). There are no intrasectoral changes or technological effects. From (3.10) and (3.11) we find:

$$Z = X = \frac{1}{\eta} L_x \tag{3.28}$$

The appendix (Section 3.7.1) shows that L_x rises over time. This implies a gradual increase in pollution and a gradual fall in innovation. The underlying cause is a fall in the rate of return to innovation. As the proportion of low-price firms increases, more labour is allocated to incumbents and less is available per quality leader that replaces a cost-leader. As a result, profits for entrants fall and innovation becomes less profitable. The paths of pollution and of the innovation rate are again depicted in Figure 3.3 (curve segments from $n_U = 0$ to $n_U = 1$).

The innovation intensity at the end of the confidence phase (when n_L approaches zero) can be solved by first substituting (3.22) and (3.24) into (3.25) to eliminate $\dot{n}_L/n_L$ and y respectively, and then setting $n_L = \dot{y} = 0$. This yields:

$$\iota = \frac{\lambda - 1}{\lambda}\frac{L}{a} - \frac{1}{\lambda}\rho \equiv \iota_{GH} \tag{3.29}$$

When only quality improvement is possible and the mass of cost leaders approaches zero, the model structure is the same as in Grossman and Helpman (1991, chapter 4). Hence, the innovation rate in (3.29) equals the innovation rate of their model (denoted by ι_{GH}).

3.4.3 Innovation and Pollution in the Alarm Phase

The economy enters the alarm phase once it starts taxing pollution. Society is aware of or alarmed about the polluting effects of using GPT 2. To mitigate the adverse effects, firms are charged a pollution tax. Provided that all sectors are at least hit once during the second period of the confidence phase, all active firms at the beginning of the alarm phase are regulated quality leaders (R-firms). To simplify matters, we assume that the alarm phase starts not until labour-cost leaders have disappeared, i.e. $n_L = 0$.

In addition, we rule out the case that it is profitable for firms to switch back to the old traditional technology. This requires that the profits from readopting GPT 1 fall short of those from further quality improvements still using GPT 2. From (3.8), we see that this requires $1 - a_{L1}w/(a_{L2}w + \tau) <$

$1 - 1/\lambda$, or after substitution of (3.9):[9]

$$\tau/w < \lambda - \eta \tag{3.30}$$

Firms still make profits and research is still profitable. Innovators develop new quality generations of the regulated products. Successful innovators become new quality leaders and set prices $p_R = \lambda(\eta w + \tau)$. No other types of innovation are undertaken, so that $L_{gk} = 0$ for $k \neq R$ and $L_{gR} + L_x = L$. The value of a blueprint is determined by v_R, and we have $aw = v_R$ if $L_{gR} > 0$.

The dynamics of the alarm phase can be determined in analogy to the dynamics of the improvement subphase of the confidence phase. Substituting (3.4) into (3.23) to eliminate r, substituting (3.10) into (3.21) to eliminate L_x, and taking into account n_R= 1, n_k= 0 for $k \neq R$, we find:

$$\frac{\dot{y}}{y} = y\frac{1}{a}\left(\frac{\lambda - 1}{\lambda} + \frac{\eta}{\lambda\left(\eta + \tau/w\right)}\right) - \left(\frac{L}{a} + \rho\right) \tag{3.31}$$

If firms expect no shocks, i.e. they do not anticipate the arrival of a new GPT or a change in taxation, equation (3.31) can only hold forever if y remains constant over time.[10] Hence, we can set (3.31) equal to zero to obtain the following expression for the steady state expenditures per wage income:

$$y = \frac{L + a\rho}{1 - \theta_{Z2}/\lambda} \tag{3.32}$$

where $\theta_{Z2} = (\tau/w)/(\eta + \tau/w)$ is the share of pollution in total cost for GPT 2. In addition, from equations (3.10), (3.21) and (3.32) the steady state innovation growth rate in the alarm phase, $\iota_{SSAlarm}$, is readily calculated as:

$$\iota_{SSAlarm} = \frac{\lambda}{\lambda - \theta_{Z2}}\left[\frac{L}{a}\left(\frac{\lambda - 1}{\lambda}\right) - \frac{\rho}{\lambda} + \frac{\theta_{Z2}}{\lambda}\rho\right] \tag{3.33}$$

[9] If $\tau/w > \lambda - \eta$, the alarm phase as described in the text does not arise and the economy enters immediately a "reswitching phase" once the tax is imposed. This phase is very similar to the cleaning-up phase analysed in the text (see section 3.4.4). The only modification needed is setting γ equal to one. When GPT 3 arrives, a adoption phase starts in which GPT 1 is replaced by GPT 3. The analysis of this phase is more complex than the one in the text since with "reswitching" there are potentially three GPTs in the market.

[10] Otherwise y would grow or shrink at an increasing rate, both of which is not feasible.

or, equivalently as:

$$\iota_{SSAlarm} = \frac{\lambda}{\lambda - \theta_{Z2}} \left[\iota_{GH} + \frac{\theta_{Z2}}{\lambda} \rho \right] \tag{3.34}$$

Note that spending per wage income and the rate of innovation increase in the pollution tax; for $\tau > 0$ we have $\iota_{SSAlarm} > \iota_{GH}$ and $(L+a\rho)/(1-(\theta_{Z2}/\lambda)) > L + a\rho$. The intuition behind this remarkable result for growth is that a pollution tax increases the cost of production relative to that of R&D. Since production with GPT 2 causes pollution, the introduction of a pollution tax increases unit production costs [see equation (3.5)]. The costs of R&D, however, are not directly affected by the implementation of a pollution tax, since R&D is a non-polluting activity. Thus, this policy intervention causes a change in the relative prices of manufacturing and R&D and, therefore, a reallocation of labour from manufacturing to the development of blueprints. Besides this (positive) substitution effect, there is also a (negative) output effect. The pollution tax increases unit production costs and thus reduces firms' profits. This mitigates the incentives to develop new blueprints, and the innovation rate decreases. Yet, the substitution effect outweighs the output effect.[11] As a result, at the beginning of the alarm phase, the rate of innovation jumps up and total emissions jump down compared to the values at the end of the confidence phase, as shown in Figure 3.3 (curve segments at $n_R = 1$). But both variables remain constant during the alarm phase.

3.4.4 Innovation and Pollution in the Cleaning-up Phase

General equilibrium dynamics

From the point of view of GPTs, the cleaning-up phase is similar to the confidence phase. A new unregulated technology is available for adoption, but its diffusion takes time, since adoption is costly. Adoption takes place

[11] In addition, since our model assumes full employment and abstracts from adjustment costs (i.e. costless and immediate switching of labour from manufacturing to R&D or vice versa) the introduction of a pollution tax does not affect the labour market in this regard.

only if the returns to the development of a blueprint for adopting GPT 3 are large enough. To guarantee sufficient incentives to adopt GPT 3 we assume:

$$\gamma < \frac{\tau/w + \eta}{\lambda}, \tag{3.35}$$

which implies $\pi_R < \pi_F$ (see Table 3.1). Regulated quality leaders stay active as long as no rival in their sector has incurred the cost to adopt GPT 3. Innovators that produce with the new GPT are first movers (F-Firms).

We can use expressions derived for the confidence phase to describe the dynamics of the cleaning-up phase. For the adoption subphase, we need to replace n_L by n_F in (3.17). Substituting (3.4) into (3.18) to eliminate r, substituting (3.10) into (3.17) to eliminate L_x, and taking into account $c_j/c_{j-1} = \gamma/(\eta + \tau/w)$, $n_R + n_F = 1$ and $n_T = n_L = n_U = n_E = 0$, we find:

$$\frac{\dot{y}}{y} = \left(1 - \frac{\gamma}{\eta + \tau/w}\right)\left(\frac{1}{a}\right) y - \rho \tag{3.36}$$

$$\dot{n}_F = \frac{L}{a} - y\left(\frac{1}{a}\right)\theta_{L2}\left[\left(\frac{\gamma}{\eta} - \frac{1}{\lambda}\right) n_F + \frac{1}{\lambda}\right] \tag{3.37}$$

where $\theta_{L2} = 1 - \theta_{Z2} = \eta/(\eta + \tau/w)$ is the labour cost share for GPT 2.

For the improvements subphase, we need to replace n_L by n_F in (3.22). Substituting (3.4) into (3.23) to eliminate r, substituting (3.10) into (3.21) to eliminate L_x, and taking into account $n_F + n_E = 1$, $n_T = n_L = n_U = n_R = 0$, we get:

$$\frac{\dot{y}}{y} = (1 - \mu_F n_F)\left(\frac{1}{a}\right) y - \left(\frac{L}{a} + \rho\right) \tag{3.38}$$

$$\frac{\dot{n}_F}{n_F} = \left(\frac{1}{\lambda} - \mu_F n_F\right)\left(\frac{1}{a}\right) y - \frac{L}{a} \tag{3.39}$$

where $\mu_F = (1/\lambda) - \gamma/(\eta + \tau/w)$.

The two dynamic systems in (3.36)-(3.39) can be depicted in a n_F, y plane similar to Figure 3.2. The equilibrium dynamics can again be characterised by a rise in n_F from 0 to 1, while y increases. After a finite time there is an endogenous switch to the improvement subphase in which both n_F and y fall over time.

Pollution and innovation

Pollution is obviously absent in the improvement subphase. Moreover, innovation falls similar to innovation in the improvement subphase of the confidence regime. Hence, we focus on what happens to pollution and innovation in the adoption subphase. Pollution is given by [see (3.11)]:

$$Z = y\left(\frac{1-n_F}{\lambda(\eta+\tau/w)}\right) \tag{3.40}$$

It turns out that pollution continuously falls over time (see Section 3.7.2 in the appendix). More and more sectors switch to the clean technology (n_F increases), which reduces pollution. The upward pressure on pollution from increases in spending y is dominated by intrasectoral shifts from dirty to clean firms. The clean F-firms are for the most part responsible for rising y, since they charge a lower price and produce more than regulated quality leaders. In this case, the composition and technique effect outweigh the pollution-using scale effect.

Labour allocated to production can be written from (3.10) as:

$$L_x = y\left(\frac{(\lambda\gamma-\eta)n_F+\eta}{\lambda(\eta+\tau/w)}\right) \tag{3.41}$$

Since y and n_F increase over time, the amount of labour in production also gradually increases if $\lambda\gamma \geq \eta$. Since the rate of innovation is negatively related to L_x, as in (3.17), innovation falls over time. This seems to be the most realistic case. It seems natural to assume that the superiority of GPT 3 over GPT 2 in terms of pollution ($a_{Z3} = 0 < a_{Z2} = 1$) comes at the cost of a higher labour requirement, that is $a_{L3} = \gamma > a_{L2} = \eta$. Since $\lambda > 1$ we have $\lambda\gamma > \eta$.[12]

The progression of both pollution and the innovation rate during the cleaning-up phase is shown in Figure 3.3 (curve segments form $n_F = 0$ to

[12] In case $\lambda\gamma < \eta$ innovation may first rise and then fall over time. In this case (3.41) is isomorphic to (3.49) so that the analyses of the appendix (Section 3.7.1) can be repeated and the pattern of innovation found there emerges.

$n_F = 1$ for the adoption subphase and from $n_E = 0$ to $n_E = 1$ for the improvement subphase). At the beginning of the adoption subphase pollution jumps down and the innovations rate jumps up compared to the values during the alarm phase. The reason for these jumps is a reallocation of labour from manufacturing to R&D. Developing blueprints for adopting GPT 3 yields a higher rate of return than developing blueprints for quality improvements.

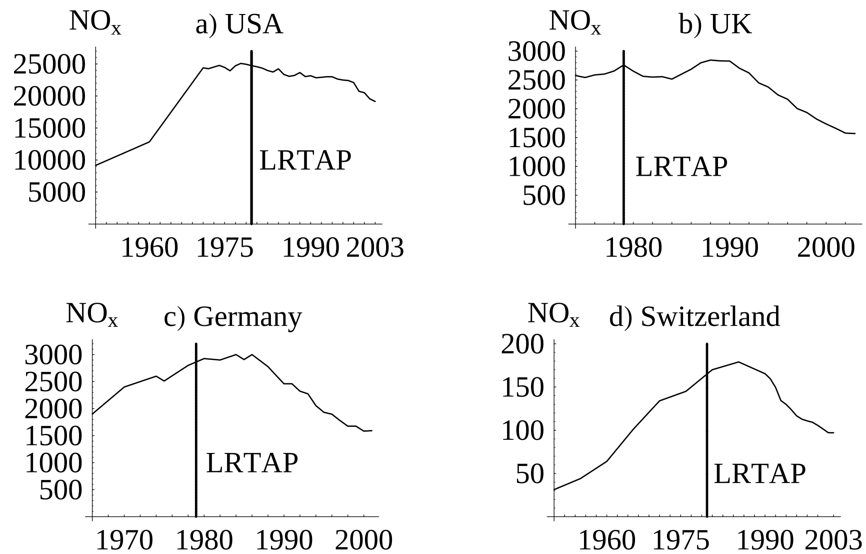
3.5 Empirical Validation

In the model analysed above, the rise in pollution is primarily caused by the availability of a new GPT, which entails lower labour costs but causes higher pollution, and an increase in aggregate production. Likewise, the downturn in pollution is based on two main mechanisms: first, the imposition of a pollution tax due to the awakening of the public's attention to environmental degradation and, second, the intrasectoral adjustments towards cleaner production technologies. These results fit fairly well with real-world observations. As an example, consider the nitrogen oxide emissions in the last decades for the USA, UK, Germany and Switzerland, as shown in Figure 3.4. It was not until the eighties of the last century that the NO_x emissions stopped increasing, and then started to decline significantly. Similar emission patterns can also be observed for other air pollutants, e.g. sulphur dioxide.

The rise in nitrogen oxide emissions was mainly caused by scale effects. For example, increasing mobility and globalisation led to drastic growth in road traffic in all four countries. Environmental degradation attracted broad public attention in the late nineteen seventies. In 1979, the countries considered signed the *Convention on Long-Range Transboundary Air Pollution* (LRTAP) of the United Nations Economic Commission for Europe. In 1988 the convention was extended by a protocol concerning the control of nitrogen oxides or their transboundary fluxes.[13] The vertical lines labelled "LRTAP"

[13] Up until 1999, the convention was extended by eight protocols aiming at the reduction of specific pollutants.

in Figure 3.4 depict the signing of the *Convention on Long-Range Transboundary Air Pollution.*



Note: NO_X emissions in Gg.

Source: USA: EPA (2000 and 2005); UK: DEFRA (2005),
Germany: DESTATIS (1966 - 2004), Switzerland: SAEFL (1995 and 2005).

Figure 3.4: NO_X for the USA, UK, Germany and Switzerland

In the subsequent years the governments enacted a number of laws to achieve the agreed emission reductions. The regulations were mainly geared to the major sources of nitrogen oxide: road transport and combustion plants. In the USA and particularly in California, catalytic converters became mandatory in the late nineteen seventies; Switzerland followed in 1987 and the European Union in 1993. This regulation has led to a gradual displacement of old motor vehicles by less exhaust-intensive vehicles with catalytic converters. In addition, the exhaust gas regulations were and are still tightened continuously. Moreover, Germany and Switzerland recently established a performance-based heavy vehicles fee, inter alia in order to confine heavy vehicle traffic. Concerning combustion plants, tightened emission restrictions led to the installation of so-called low nitrogen oxides burners, which can reduce emissions by up to 30%. Summarising, the NO_x emission reductions can be traced back to the interaction of governmental regulation, intrasectoral substitution processes and the adoption of new, cleaner technologies.

3.6 Conclusions

To analyse the relationship between economic growth, environmental degradation and technology changes, we have set up a Schumpeterian endogenous growth model with pollution. The model contributes to the literature by, first, treating the direction of technological change as endogenous, i.e. innovation opportunities and incentives determine whether technological change is pollution-using or pollution saving. Second, the model stresses the importance of intrasectoral – rather than intersectoral – shifts as a leading cause for the resulting pollution-income relation.

At first, a technological breakthrough in the form of a new general purpose technology gives rise to the gradual adoption of this new technology by profit maximising firms. As a side-effect, pollution rises. Once pollution taxes are imposed to address the pollution externality, the pattern of technological change and innovation is affected. Due to the emission taxation it becomes profitable for firms to adopt a new, clean GPT. This results in a gradual decrease of pollution associated with the use of the previous GPT.

We have shown that the gradual adoption of new general purpose technologies, which leads to intrasectoral shifts from clean to dirty firms or vice versa, predicts a pattern of pollution over time that is consistent with the EKC hypothesis. New technologies sometimes increase pollution, and decrease pollution at other times, depending on the characteristics of the general purpose technology that opens up opportunities for innovation and on the environmental policies that are in place. Our investigation of the relationship between innovation and pollution shows that we cannot expect an unambiguous correlation between changes in pollution and innovation, since both variables are endogenous and determined by several forces that act simultaneously. When pollution is not taxed (during the confidence phase), pollution rises while innovation falls over time; but during adoption of the clean technology (cleaning-up phase), both pollution and innovation decline over time. Hence, the relationship between environmental policy and economic growth varies with the different stages of growth.

The model set up above does not necessarily predict an EKC for all pollutants. In empirical research, the EKC is found only for specific pollutants, i.e. for pollutants with local and immediate effects. In our model, the downward sloping part of the EKC emerges only if the polluting GPT is eventually replaced by a cleaner GPT. The adoption of the cleaner GPT requires sufficient incentives, i.e. a high pollution tax or low enough labour costs associated with the clean GPT. Otherwise, no technology shift takes place and the pollution tax only has the conventional static (level) effect. In this case, the economy would remain in the alarm phase.

Our model provides a natural framework for the examination of the idea of overlapping EKCs. Booth (1998) has argued quite strongly that one pollutant can only be phased out because it is replaced by another pollutant. Put more moderately, it could be that seemingly clean GPTs turn out to be polluting in the end. If this is the case, additional GPTs have to be developed in a row until finally, hopefully, one GPT really turns out to be clean. In the model, the substitution of a pollutant for another would result in an overlapping of the cleaning-up phase with a second confidence phase.

An obvious extension of the model would be the possible ability of individuals to expect the arrival of new GPTs. For example, we could assume that the occurrence of new GPTs follows a Poisson process. It is conceivable that, for certain pollutants, technical solutions in the future can be anticipated to a certain degree. In other cases, however, it seems reasonable to assume that the arrival of a technological breakthrough is highly uncertain and arrives, if ever, unexpectedly. In addition, the sequencing of the different phases can be more complex than modelled in this approach. Arrival dates of profitable GPTs and/or the introduction of taxes can be assumed to occur at different points in time so that more types of producers are active in the markets when a new phase begins. Finally, one could elaborate more on optimal taxation. This requires the analysis of instruments to correct pollution, to correct R&D, and to correct output levels in order to remove the distortionary pricing effects. All these issues are left for future research.

3.7 Appendix

3.7.1 Pollution and Innovation in the Confidence Phase

To find out the development of aggregate pollution and the rate of innovation in the confidence phase, we transform the phase diagram from Figure 3.2 and equations (3.19), (3.20), (3.24) and (3.25) into a phase diagram in the L_x, n_L plane.

Adoption subphase

L_x may either fall or rise during the adoption subphase, depending on whether η is small or large respectively. From (3.10) we find the following expression for L_x in the confidence adoption subphase:

$$L_x = y\left(\frac{1-(1-\lambda\eta)n_L}{\lambda}\right) \tag{3.42}$$

We use (3.42) to replace y in (3.19) and (3.20) by L_x and find the following dynamic system for the adoption subphase:

$$\begin{aligned} \frac{\dot{L}_x}{L_x} &= \frac{1}{a[1-(1-\lambda\eta)n_L]} \\ &\quad \cdot \{[\lambda(1-\eta)+1-\lambda\eta]L_x-(1-\lambda\eta)L-[1-(1-\lambda\eta)n_L]a\rho\} \end{aligned} \tag{3.43}$$

$$\dot{n}_L = \frac{1}{a}(L-L_x) \tag{3.44}$$

The $\dot{L}_x = 0$ locus is downward sloping as long as $1/\lambda > \eta$ which is the case due to our assumption that $\mu \equiv 1/\lambda - \eta > 0$ (to ensure that $\pi_L > \pi_T$). The initial jump in L_x is determined in the same way as that of y, see main text: the endvalue of L_x is determined by its initial value in the subsequent improvement subphase. However, we can also use the endvalue of y to determine the end value of L_x by using the relation between these two variables given by (3.42). Hence, we can infer some useful properties of the endvalue of L_x from the endvalue of y. From Figure 3.1 or (3.19) we see that when $n_L = 1$, y is bounded as follows:

$$y < \frac{1}{1-\mu}(L + a\rho) \tag{3.45}$$

Thus, from (3.42) we see that when $n_L = 1$, L_x is bounded as follows:

$$L_x < \frac{\eta}{1-\mu}(L + a\rho) \tag{3.46}$$

From (3.43) we see that when $n_L = 1$,we have

$$\dot{L}_x \leq 0 \quad \text{if} \quad L_x \leq \frac{\mu L + \eta a\rho}{\mu + 1 - \eta} \tag{3.47}$$

Now consider the following condition:

$$\frac{\eta}{1-\mu}(L + a\rho) \leq \frac{\mu L + \eta a\rho}{\mu + 1 - \eta} \tag{3.48}$$

If condition (3.48) holds, L_x has to reach a value at the end of the adoption phase that turns out to be so small [namely smaller than the expression at the LHS of (3.48), see (3.46)] that it can only be reached by a declining L_x [as is revealed by (3.47)]. Note that for sufficiently low values of η this condition is satisfied. Figure 3.5 c) depicts this situation.

Let us now consider the opposite case in which η takes its maximal value, that is $\eta = 1/\lambda$ so that $\mu = 0$. The d$y = 0$ locus and the d$L_x = 0$ locus are horizontal. Moreover, y and L_x have to reach the values $L + a\rho$ and $(L + a\rho)/\lambda$ respectively at the end of the adoption subphase. Under our assumption that $\iota_{GH} > 0$, see (3.29), this endpoint lies above the d$L_x = 0$ locus, see (3.43), and L_x has to increase over the entire adoption subphase. Figure 3.5 a) depicts this situation.

For intermediate values of η we get the dynamics as depicted in Figure 3.5 b). The larger η, the more likely a rising pattern for L_x becomes. Note that L_x may first fall and then rise (but never the other way around) in the adoption subphase.

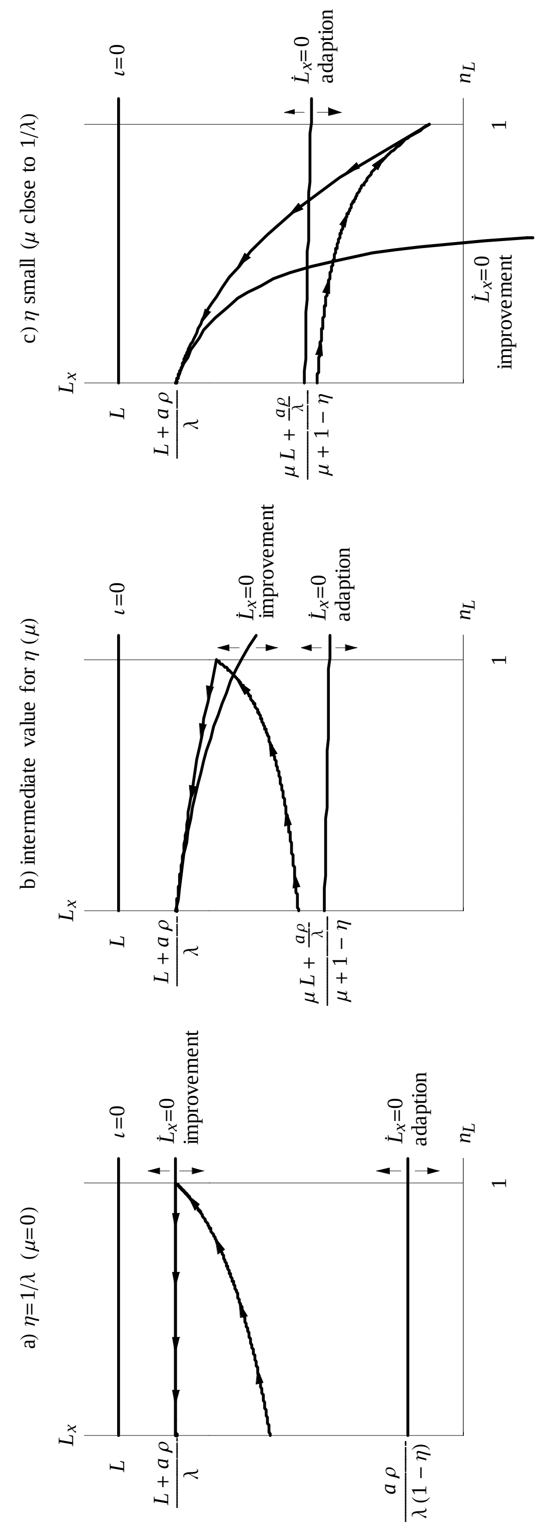


Figure 3.5: Dynamics confidence phase in the n_L, L_x plane

Improvement subphase

We show that L_x unambiguously falls during the improvement subphase. For this subphase, we find from (3.10):

$$L_x = \left(\frac{1}{\lambda} - \mu n_L\right) y \tag{3.49}$$

We use (3.49) to replace y in (3.24) and (3.25) by L_x and find the following dynamic system for the improvement subphase:

$$\begin{aligned}\frac{\dot{L}_x}{L_x} &= \frac{1}{a(1/\lambda - \mu n_L)} \\ &\quad \cdot \{[1 - 2\mu n_L]L_x - [1/\lambda - 2\mu n_L]L - [1/\lambda - \mu n_L]a\rho\}\end{aligned} \tag{3.50}$$

$$\frac{\dot{n}_L}{n_L} = -\frac{1}{a}(L - L_x) \tag{3.51}$$

The $\dot{L}_x = 0$ locus is downward sloping. Since the improvement subphase starts at $n_L = 1$ and has to converge to a constant value for L_x and $n_L = 0$, L_x has to start at a value above the $\mathrm{d}L_x = 0$ locus and will increase over time. Figure 3.5 combines the two subphases.

The development of pollution in the improvement subphase directly follows from (3.28) and the notion that L_x rises over time. The development of the rate of innovation is the mirror image of that of L_x, since $\iota = (L - L_x)/a$.

3.7.2 Pollution in the Cleaning-up Phase

We transform the dynamic system in (3.36)-(3.37) into a dynamic system in terms of Z and n_R. Substituting (3.40) in these equations to eliminate y, and replacing n_F by $1 - n_R$, we find:

$$\frac{\dot{Z}}{Z} = \frac{(\xi + \lambda\gamma/n_R)Z - L - a\rho n_R}{a n_R} \tag{3.52}$$

$$\frac{\dot{n}_R}{n_R} = -\frac{L - [\lambda\gamma/n_R - (\lambda\gamma - \eta)]Z}{a n_R} \tag{3.53}$$

where $\xi = \eta + (\lambda - 1)(\tau/w + \eta) + [\tau/w + \eta - \lambda\gamma] - \lambda\gamma$. Note that $\xi > -\lambda\gamma$ from our assumptions made above to ensure adoption of the clean GPT [the term in square brackets is positive, see (3.35)].

We now have two situations, depending on whether ξ is positive or negative. First, if it is positive, the $\mathrm{d}Z = 0$ locus slopes positive in the feasible region (for $0 < n_R < 1$) and the saddlepath slopes downward so that pollution unambiguously falls with the fall in n_R. Figure 3.6 shows the phase diagram for this case. Second, if ξ is negative, the $\mathrm{d}Z = 0$ locus has a vertical asymptote at $n_R = -\lambda\gamma/\xi > 1$ and slopes downward in the feasible range (for $0 < n_R < 1$). However, the saddlepath slopes downward so that again pollution unambiguously falls with the fall in n_R. The corresponding phase diagram would resemble the one shown in Figure 3.6.

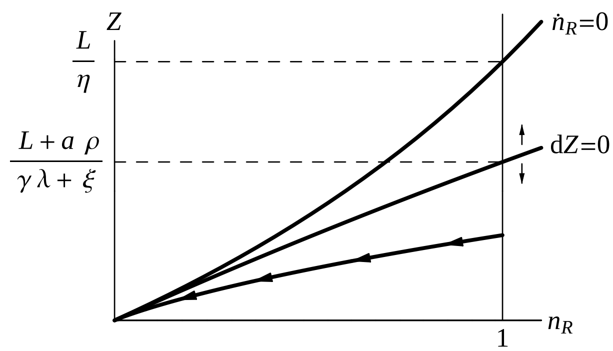


Figure 3.6: Dynamics cleaning-up phase in the n_R, Z plane

Chapter 4

A Dynamic Model of the Environmental Kuznets Curve: Turning Point and Public Policy*

We set up a simple dynamic macroeconomic model with (i) polluting consumption and a preference for a clean environment, (ii) increasing returns in abatement giving rise to an EKC and (iii) sustained growth resulting from a linear final-output technology. The model captures two sorts of market failures caused by external effects associated with consumption and environmental effort. This model is employed to investigate the determinants of the turning point and the (relative) effectiveness of different public policy measures aimed at a reduction of the environmental burden. Moreover, the model offers a potential explanation of an N-shaped pollution-income relation. Finally, it is shown that the model is compatible with most empirical regularities on economic growth and the environment.

*Forthcoming in *Environmental & Resource Economics*. This chapter represents joint work together with Thomas M. Steger (ETH Zurich).

4.1 Introduction

The Environmental Kuznets Curve (EKC) hypothesis states that there is an inverted U-shaped relationship between environmental degradation and the level of income. Starting with Grossman and Krueger (1993) this pattern has been intensively debated in empirical terms; recent reviews are provided by Dasgupta et al. (2002) and Stern (2004). The EKC has also captured considerable attention from policymakers and theorists. This is due to the fact that the EKC hypothesis implies that pollution diminishes once a critical threshold level of income is reached. As a consequence, there is the hope that – loosely speaking – the environmental problem sooner or later peters out as the economy grows.

There are two major strands within the theoretical EKC literature. In the first class of models an EKC arises from shifts in the use of production technologies, which differ in their pollution intensity (Stokey, 1998; Chapter 3 of this study). The second class focuses on the characteristics of the abatement technology (John and Pecchenino, 1994; Selden and Song, 1995; Andreoni and Levinson, 2001; Chimeli and Braden, 2002; Brock and Taylor, 2004).

The Andreoni and Levinson (2001) model has attracted a significant attention. Using a static setup, they show that an EKC can be explained with increasing returns to scale (IRS) in the abatement technology. Moreover, Andreoni and Levinson (2001) claim that by focusing on the degree of returns to scale in abatement, a large part of the literature dealing with very different mechanisms (e.g. a shift in technology or a shift in institutions) can be summarised.

The level of income at which pollution peaks (labelled "the turning point") and the associated level of pollution are of fundamental interest from the perspective of public policy. A sound understanding of the pollution-income relation (PIR) could provide important information for public policies aimed at a reduction of the environmental burden. The empirical EKC literature has accordingly devoted much effort to the determination of this critical threshold.

The results show, however, a large dispersion across different studies. For instance, the reported turning points for sulphur dioxide range from \$2,900 to \$908,200 and for nitrogen oxides from \$5,500 to \$30,800 (in 1985 PPP\$; Lieb, 2003). Given these diverse empirical results, it is clearly desirable to better understand the determinants of the turning point from a theoretical perspective.

In this paper, we set up a simple dynamic EKC model, which has the following characteristics: Pollution is a by-product of consumption activities, it is modelled as flow pollution and it creates disutility. Households can spend resources on abatement to reduce net pollution. Following Andreoni and Levinson (2001) we assume that there are IRS in abatement giving rise to an EKC. There are two market distortions due to external effects associated with consumption and abatement activities. Permanent growth results from an accumulable stock of capital and a linear final-output technology.

The paper at hand focuses on two issues: First, we employ the simple dynamic EKC model to better understand the determinants of the turning point. The factors which are of major interest in this type of models are the preference for a clean environment, the degree of IRS in abatement and the magnitude of external effects. Second, we investigate the effectiveness of public policy measures aimed at a reduction of the environmental burden. In this context, it is important to have a model with multiple market failures so that the question of the relative effectiveness of different environmental policy measures can be answered.

As noted above, pollution is modelled as flow pollution. The reason lies in the fact that an EKC is more likely to arise for flow pollutants than for stock pollutants. This is best illustrated by Lieb (2004, p. 484) who reports that "*almost all studies agree that there is an EKC for sulphur dioxide (SO_2), suspended particulate matter (SPM), oxides of nitrogen (NO_x), carbon monoxide (CO), and for some (but not all) sorts of river pollution (PR)... Although all these pollutants are stock pollutants, they all have short life-times and can therefore be considered as flow pollutants from a long-run point of view.*"

Turning to the related literature, there are a number of theoretical papers on the EKC which consider the determinants of the turning point; some of these papers also investigate the role of public policies. Brock and Taylor (2004) use an augmented Solow model to demonstrate that an EKC arises along the transition to the steady state. Although there is polluting production in this model, there is no market failure. Lieb (2004) uses an overlapping generations model with a stock pollution and a flow pollution. He focuses on the different pollution paths of the stock and the flow pollution. The model captures several external effects associated with production and abatement. However, only the problem of a myopic government is analysed implying that the intragenerational externalities are internalised, while the intergenerational externalities are not. Moreover, the effectiveness of public policy measures is not considered since the unregulated market economy is not investigated. Chimeli and Braden (2002) employ a simple endogenous growth model with environmental quality. The authors show that environmental quality follows a V-shaped pattern, thereby explaining an EKC for a stock pollution. There is single external effect associated with polluting production. Hence, the consequences of multiple external effects cannot be studied. Finally, Anderson and Cavendish (2001) employ a dynamic simulation model to investigate the consequences of public policy measures on the turning point. This computable equilibrium model has the advantage of being able to directly include different aspects of the real world which are important in this context. However, general equilibrium feedback effects are excluded and optimal taxes cannot be derived.

The remainder of this paper is organised as follows: In Section 4.2, the basic Andreoni and Levinson (2001) model is sketched. In Section 4.3, a simple dynamic EKC model is set up in general form. The decentralised and the centralised solution are investigated and the optimal tax scheme is determined. In Section 4.4, a parameterised version of the model is employed to investigate the determinants of the turning point and the relative effectiveness of different public policies. In Section 4.5, it is shown that an N-shaped

PIR can potentially be explained from the interaction of public policy and the intrinsic properties of the model. Section 4.6 demonstrates concisely that the model is compatible with most sets of stylised facts on economic growth and the environment. Finally, Section 4.7 summarises the main results and concludes.

4.2 The Andreoni and Levinson EKC Model

In an important paper, Andreoni and Levinson (2001) set up a simple static model to derive sufficient conditions for an EKC. The Andreoni and Levinson model is sketched below to provide a reference point for the following discussion.

Utility of the representative agent depends positively on consumption C and negatively on pollution P. The general utility function may be expressed as:

$$U = U(C, P). \tag{4.1}$$

Pollution is a function of consumption and environmental effort E according to:

$$P = C - B(C, E). \tag{4.2}$$

Pollution increases one-to-one with consumption (gross pollution) as represented by the first term on the RHS. On the other hand, pollution decreases due to abatement as represented by the second term of the RHS. $B(C, E)$ is the abatement technology, which is increasing in both arguments. Both "inputs" are essential for abatement, i.e. $B(0, E) = B(C, 0) = 0$. The final basic equation is a standard budget constraint given by $M = C + E$, where M denotes the available resources (income).

Andreoni and Levinson (2001, p. 277) show that there are two conditions which together guarantee the existence of an EKC. The first condition – related to preferences – states that "*the marginal willingness to pay to clean up* *the last speck of pollution does not go to zero as income approaches infinity*". This is a rather weak condition; it is easily satisfied since pollution abatement can be regarded as a normal good.[1] The second condition – related to the abatement technology – states that there must be IRS in abatement.

Using the following parameterisation $U(C,P) = C - zP$ with $z = 1$ and $B(C,E) = C^{\alpha}E^{\beta}$, Andreoni and Levinson (2001) show that an EKC results provided that $\alpha + \beta > 1$. This can be immediately recognised by inspecting the pollution function in terms of M:

$$P(M) = \frac{\alpha}{\alpha+\beta}M - \left(\frac{\alpha}{\alpha+\beta}\right)^{\alpha}\left(\frac{\beta}{\alpha+\beta}\right)^{\beta}M^{\alpha+\beta}. \tag{4.3}$$

The preceding equation results from $P = C - C^{\alpha}E^{\beta}$, $C^* = \frac{\alpha}{\alpha+\beta}M$ and $E^* = \frac{\beta}{\alpha+\beta}M$, where C^* and E^* are the optimal level of consumption and environmental effort. Equation (4.3) implies that $P(M)$ is concave in M provided that $\alpha + \beta > 1$. Hence, IRS in abatement (defined by $\alpha + \beta > 1$) represent a necessary condition for the existence of an EKC.

4.3 A General Dynamic EKC Model

In this section, we set up a simple dynamic EKC model, which will be employed in the course of this paper. Pollution results as a by-product of consumption activities and is modelled as flow pollution. Households can reduce pollution by spending resources on abatement. The abatement technology is characterised by IRS. As Andreoni and Levinson (2001) have shown, this assumption leads to an EKC. There is a homogeneous final-output good which is produced under constant returns to scale using (physical and human) capital as the sole input factor. Households earn income by renting capital to firms. Output and factor markets are perfectly competitive. We consider two types of externalities and hence the decentralised solution diverges from

[1] Lieb (2002) shows that the normality of environmental quality is a necessary condition for the existence of an EKC.

the centralised solution. At first, the market economy is considered and subsequently the centralised solution is investigated. Finally, the optimal tax scheme is determined.[2]

4.3.1 The Decentralised Economy

There is a large number of identical households ordered on the interval $[0, 1]$. The representative household derives utility from consumption C and disutility from net pollution P. The instantaneous utility function is $U(C, P)$ with $U_C > 0$, $U_{CC} < 0$, $U_P < 0$ and $U_{PP} < 0$.[3] The flow of pollution (per period of time) is given by the difference between gross pollution $G(C, \bar{C})$ and abatement $B(C, E, \bar{E})$:

$$P(C, \bar{C}, E, \bar{E}) = G(C, \bar{C}) - B(C, E, \bar{E}), \tag{4.4}$$

where E is environmental effort and a "bar" above a variable denotes its economywide average. The above-stated pollution function shows that pollution is modelled to result from consumption.[4] Direct examples for polluting consumption activities would be the use of automobiles and central heating. Turning to environmental effort, we can interpret the model in the sense that both households as well as firms conduct abatement. It is plausible and convenient to let the incidence of abatement costs fall on households. To clarify this aspect, consider a real-world example: Abatement in the case of driving automobiles comprises the installation of catalytic converters and strainers. Although the major part of this abatement activity (development and installation) is conducted by firms, households face the decision for, and bear the costs of this environmental effort.

[2]There are other general growth models with pollution and external effects (e.g. Smulders and Gradus, 1996).

[3]We do not restrict the cross derivatives at this stage.

[4]More frequently, pollution is modelled as a by-product of production (e.g. Xepapadeas, 2004). There are, however, other theoretical studies, beside Andreoni and Levinson (2001), which assume that consumption generates pollution (e.g. John and Pecchenino, 1994).

There are two kinds of externalities, which both build on the assumption that there is no strategic interaction between households – in terms of making allowance for interdependence between own and others' actions. First, the representative household takes the polluting effects of consumption only partly into account. It does not consider that the other households are also negatively affected by its consumption. In other words, there is a (negative) pollution externality associated with consumption. Second, environmental effort aimed at reducing (net) pollution also affects the society as a whole, i.e. there is a (positive) externality resulting from environmental effort. Again, the representative household neglects that its environmental effort has a positive impact on the other households, as well. As an example, consider again the use of automobiles. It is the household who bears the financial burden, but it is society that primarily benefits from the implementation of catalytic converters and filters. External effects are associated with the economy-wide averages of consumption $\bar{C}$ and environmental effort $\bar{E}$, which are considered exogenous from the perspective of the typical household.

As noted above, households earn capital income only. Let r denote the rental price of capital and K the stock of capital owned by households. Then the household's income is simply rK. The household's gross expenditures (including taxes) are given by $(1+\tau_C)C+(1+\tau_E)E$, where τ_C and τ_E represent taxes (or subsidies) on consumption and environmental effort.[5] Overall tax revenues T are redistributed in a lump-sum manner according to a balanced-budget rule, i.e. $T = \tau_C C + \tau_E E$. Households are assumed to maximise the present value of an infinite utility stream. The associated dynamic problem may be expressed as follows (time index suppressed):

$$\max_{\{C,E\}} \int_0^\infty U(C,P)e^{-\rho t}\,dt \tag{4.5}$$

$$\begin{aligned} s.t. \quad P(C,\bar{C},E,\bar{E}) &= G(C,\bar{C}) - B(C,E,\bar{E}) && (4.6)\\ \dot{K} &= rK - (1+\tau_C)C - (1+\tau_E)E + T && (4.7)\\ K(0) &= K_0, && (4.8) \end{aligned}$$

[5] Optimal tax rates are determined below.

where ρ denotes the time preference rate, t the time index, $\dot{K}$ the rate of change of K per period of time and K_0 is the initial stock of capital, respectively. Notice that equation (4.7) shows the flow budget constraint of the typical household.

As mentioned above, the focus here is on flow pollution. Because a pure flow pollution (i.e. there is no pollution stock) cannot become negative, the technical restriction $P \geq 0$ must be taken into account (see also Lieb, 2004, p. 488). Moreover, since we are interested in an inverted U-shaped PIR, attention is restricted to interior solutions. The dynamic problem above can be easily extended to allow for border solutions with $P = 0$.

The (current-value) Hamiltonian for the above-stated problem reads as follows:

$$H = U[C, P(C, \bar{C}, E, \bar{E})] + \lambda[rK - (1 + \tau_C)C - (1 + \tau_E)E + T], \qquad (4.9)$$

where λ denotes the shadow price of capital. The necessary first-order conditions are given by:[6]

$$\frac{U_C + U_P P_C}{1 + \tau_C} = \lambda \qquad (4.10)$$

$$\frac{U_P P_E}{1 + \tau_E} = \lambda \qquad (4.11)$$

$$\dot{\lambda} = -\lambda(r - \rho), \qquad (4.12)$$

where U_x and P_x denote the partial derivatives of U and P with respect to $x \in \{C, E\}$, respectively. For ease of interpretation, assume for the moment that $\tau_C = \tau_E = 0$. Equation (4.10) then shows that along the optimal growth path the (private) marginal utility of consumption must equal the shadow price of capital λ. The marginal utility of consumption comprises two components: (i) the direct utility from consumption U_C and (ii) the disutility from pollution $U_P P_C$. Moreover, it should be remembered that P_C captures a gross pollution

[6] In addition, the transversality condition $\lim_{t\to\infty} e^{-\rho t}\lambda K = 0$ must hold. Moreover, we assume that the necessary conditions are also sufficient for a maximum of the utility functional.

effect G_C and an abatement effect B_C. Similarly, equation (4.11) indicates that marginal utility from environmental effort $U_P P_E$ must equal the shadow price of capital. Equation (4.12) shows that if the growth condition holds (i.e. $r - \rho > 0$), the shadow price of capital vanishes at the rate $r - \rho$.

Turning to the firm side of the economy, there is a large number of final-output firms. The representative final-output firm produces a homogeneous good using capital as the sole input factor.[7] The constant returns to scale technology is $Y = AK$, where Y is final output, K the stock of capital and A a constant technology parameter. Capital depreciates at constant rate $\delta \geq 0$. From the solution to the firm's static optimisation problem one gets:

$$r = A - \delta.$$

4.3.2 The Centralised Economy

The social planner maximises the welfare of the representative individual. This requires, of course, that the external effects are taken into account. The social planner's problem may be expressed as follows:

$$\max_{\{C,\bar{C},E,\bar{E}\}} \int_0^\infty U(C,P)e^{-\rho t}\, dt \tag{4.13}$$

$$\begin{aligned} s.t.\quad P(C,\bar{C},E,\bar{E}) &= G(C,\bar{C}) - B(C,E,\bar{E}) && (4.14)\\ \dot{K} &= F(K) - \delta K - C - E && (4.15)\\ K(0) &= K_0. && (4.16)\end{aligned}$$

The (current-value) Hamiltonian reads as follows:

$$H = U[C, P(C,\bar{C},E,\bar{E})] + \lambda[F(K) - \delta K - C - E] \tag{4.17}$$

and the necessary first-order conditions are given by:[8]

[7] As noted above, capital should be interpreted broadly to comprise human as well as physical capital.

[8] Once again, the transversality condition $\lim_{t\to\infty} e^{-\rho t}\lambda K = 0$ must hold and we assume that the necessary conditions are also sufficient.

$$U_C + U_P(P_C + P_{\bar{C}}) = \lambda \tag{4.18}$$

$$U_P(P_E + P_{\bar{E}}) = \lambda \tag{4.19}$$

$$\dot{\lambda} = -\lambda(F_K - \delta - \rho). \tag{4.20}$$

Comparing the first-order conditions (4.18) and (4.19) to the first-order conditions (4.10) and (4.11) shows the differences between the centralised solution and the decentralised solution. When deciding on the optimal levels of consumption C and environmental effort E the social planner, in contrast to the private agent, takes the external consequences associated with average consumption $\bar{C}$ and average environmental effort $\bar{E}$ into account. Specifically, the social planner considers also the effects of average consumption on gross pollution ($U_P P_{\bar{C}} = U_P G_{\bar{C}}$) as well as the consequences of average environmental effort on abatement ($U_P P_{\bar{E}} = -U_P B_{\bar{E}}$).

4.3.3 Optimal Tax Scheme

Optimal taxes τ_C^* and τ_E^* result from the comparison between the first-order conditions of the social planner's solution [(4.18) and (4.19)] and the first-order conditions of the decentralised solution [(4.10) and (4.11)]. It can be readily shown that an optimal tax scheme is given by:

$$\tau_C^* = -\frac{U_P P_{\bar{C}}}{U_C + U_P(P_C + P_{\bar{C}})} > 0 \tag{4.21}$$

$$\tau_E^* = -\frac{P_{\bar{E}}}{P_E + P_{\bar{E}}} < 0. \tag{4.22}$$

Let us start with the interpretation of τ_E^*, which is straightforward. Equation (4.22) shows that the optimal subsidy on environmental effort equals the ratio of the external marginal effect of environmental effort on pollution $P_{\bar{E}} < 0$ and the overall (i.e. private and external) marginal effect of environmental effort on pollution $P_E + P_{\bar{E}} < 0$. Similarly, the optimal consumption tax τ_C^* [equation (4.21)] is the ratio of the external marginal consumption effect on utility $U_P P_{\bar{C}} < 0$ and the overall marginal effect of consumption on utility given by $U_C + U_P(P_C + P_{\bar{C}}) > 0$.[9]

Consider finally the consequences of a tax on consumption $\tau_C > 0$ on the decisions of the representative household. A consumption tax $\tau_C > 0$ reduces the LHS of equation (4.10). Holding the shadow price of capital constant, equation (4.10) then requires that the marginal utility of consumption must increase. This can be accomplished by reducing the level of consumption. An analogous interpretation (with $\tau_E < 0$) applies to equation (4.11).

4.4 A Specific Dynamic EKC Model

In this section, a parameterised version of the model is employed to investigate the determinants of the turning point and the effectiveness of public policy. At first, we consider the centralised solution with $z = 1$. Subsequently, we turn to the more relevant case of an unregulated/imperfectly regulated economy with $z < 1$.

4.4.1 Parameterisation

For further investigations we parameterise instantaneous utility $U(C, P)$, gross pollution $G(C, \bar{C})$ and abatement $B(C, E, \bar{E})$. The following functional forms are assumed:

$$U(C, P) = \log(C - zP) \quad \text{with} \quad z > 0,\, C \geq zP \tag{4.23}$$

$$G(C, \bar{C}) = C^{\phi} \bar{C}^{\omega} \quad \text{with} \quad 0 < \phi, \omega, < 1 \tag{4.24}$$

$$B(C, E, \bar{E}) = C^{\alpha} E^{\beta} \bar{E}^{\upsilon} \quad \text{with} \quad 0 < \alpha, \beta, \upsilon < 1, \tag{4.25}$$

where z reflects the desire for a clean environment. A lower value of z means that a given amount of pollution causes less disutility and individuals will accordingly spend more on consumption and less on environmental effort. Turning to the gross pollution function (4.24), C^{ϕ} represents the internal

[9] Notice that $U_C + U_P(P_C + P_{\bar{C}}) = \lambda > 0$.

effect of consumption on gross pollution and $\bar{C}^{\omega}$ is the corresponding external effect. We assume throughout the paper that $\omega + \phi = 1$, which implies a linear gross pollution function.[10] Similarly, E^{β} is the private and $\bar{E}^{v}$ the external effect of environmental effort in abatement.[11]

A short explanation of the instantaneous utility function (4.23) is indicated. Since $\phi + \omega = 1$ and taking into account $C = \bar{C}$ and $E = \bar{E}$, pollution is given by $P = C - C^{\alpha}E^{\beta+v}$. Moreover, assuming $z = 1$ the utility function becomes $U[C, P(C, E)] = \log(C^{\alpha}E^{\beta+v})$. This formulation has the advantage that C and E enter utility additively separable, which enables an analytical solution for the social planner's problem. Two issues should be noticed in this respect: First, the preceding utility function requires $C - zP \geq 0$, otherwise utility would not be defined. For $z \leq 1$ this restriction is automatically satisfied since C is gross pollution and P is net pollution (gross pollution minus abatement). Second, the utility function implies $U_{CP} = \frac{1}{(C-zP)^2} > 0$. This property appears counterintuitive at first glance. However, this is due to the fact that a rise in P has the same effect as a reduction in C and hence marginal utility of consumption increases with pollution P.[12]

4.4.2 Analytical Results

The PIR is derived analytically and determinants of the turning point are discussed. Here we focus on the centralised solution and assume that $z = 1$. This allows us to derive analytical results. The decentralised solution with $z < 1$ is investigated in a second step by simulating the transition process (Section 4.4.3).

[10] In addition, this restriction enables us to solve the differential equation system resulting from the centralised solution analytically.

[11] The appendix on page 120 shows that the parameterised Hamiltonian functions are concave, i.e. the necessary conditions are also sufficient for a maximum of the utility functional.

[12] According to Michel and Rotillon (1995) $U_{CP} > 0$ can be interpreted as a compensation effect; consumption desire rises with pollution.

The time path of pollution $P(t)$ and the PIR $P(Y)$

From the first-order conditions [(4.18) to (4.20)] and the parameterised functions [(4.23) to (4.25)], one obtains the following solutions for K and λ:

$$K = K_0 e^{(A-\delta-\rho)t} \tag{4.26}$$

$$\lambda = \frac{\alpha+\beta+\upsilon}{K_0\rho} e^{-(A-\delta-\rho)t}. \tag{4.27}$$

Using equations (4.18), (4.19) and (4.27) and noting equations (4.23) to (4.25), one can formulate an analytical expression for the time path of pollution:

$$\begin{aligned} P(t) \;=\; & \frac{K_0 e^{(A-\delta-\rho)t}\alpha\rho}{\alpha+\beta+\upsilon} - \left[\left(\frac{K_0 e^{(A-\delta-\rho)t}\alpha\rho}{\alpha+\beta+\upsilon}\right)^{\alpha}\right. \\ & \left.\cdot \left(\frac{K_0 e^{(A-\delta-\rho)t}(\beta+\upsilon)\rho}{\alpha+\beta+\upsilon}\right)^{\beta+\upsilon}\right]. \end{aligned} \tag{4.28}$$

Furthermore, the PIR may be expressed as follows:

$$P(Y) = cY - (cY)^{\alpha}(hY)^{\beta+\upsilon}, \tag{4.29}$$

where $c := \frac{C}{Y}$ is the consumption rate and $h := \frac{E}{Y}$ the "environmental effort rate". To determine c and h, we consider the growth rate of capital $\hat{K} := \frac{\dot{K}}{K}$ using equations (4.15), (4.25) and (4.26):

$$\hat{K} = A - \delta - \rho = A - \delta - \frac{C}{K} - \frac{E}{K}. \tag{4.30}$$

Together with the parameterised versions of (4.18) and (4.19) this immediately yields the balanced growth values of the consumption rate c and of the environmental effort rate h to read as follows:

$$c = \frac{\alpha\rho}{A(\alpha+\beta+\upsilon)} \qquad \text{and} \qquad h = \frac{(\beta+\upsilon)\rho}{A(\alpha+\beta+\upsilon)}. \tag{4.31}$$

The PIR is illustrated in Figure 4.1 (a) and the time path of pollution in Figure 4.1 (b). These figures are based on the baseline set of parameters, which is set out in Section 4.4.3 below. As in Andreoni and Levinson

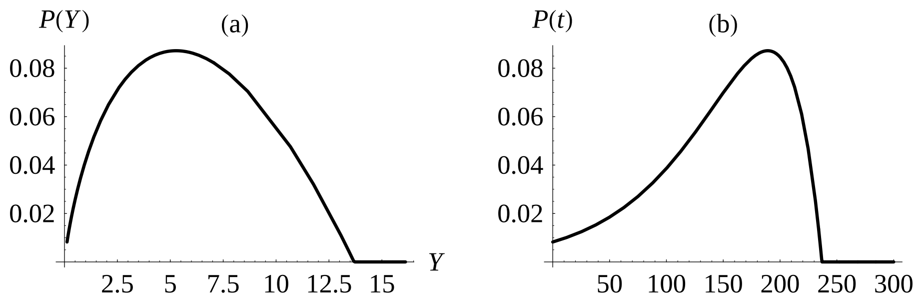


Figure 4.1: $P(Y)$ and $P(t)$ with IRS in abatement $(\alpha + \beta + \upsilon > 1)$

(2001), IRS in abatement is a necessary condition for a hump-shaped PIR.[13] Figure 4.1 (a) shows that pollution first rises with income, then declines and eventually becomes zero. This EKC represents a balanced growth phenomenon.[14] Although pollution does not grow at a constant rate (as is required by the definition of a balanced growth path), the illustrated pollution path represents a balanced growth phenomenon since pollution results from two endogenous variables (consumption and environmental effort), which both grow at constant rates. The required time span until pollution reaches its peak and becomes zero is quite long. The whole "EKC story" takes nearly 250 years as is displayed in Figure 4.1 (b).

The EKC pattern displayed in Figure 4.1 (a) is in line with empirical evidence as reported by Grossman and Krueger (1995) according to which the PIR is asymmetric with an upper tail that declines relatively gradually.

The turning point

As has been noted above, the level of income at which pollution peaks and the associated level of pollution is of outstanding interest from the perspective of

[13]In a more general version of the Andreoni and Levinson (2001) model Plassmann and Khanna (2004, p. 16) show that "*for non-constant returns to scale in gross pollution, a sufficient condition for pollution to decline is rather that the returns to scale in abatement exceed the returns to scale in gross pollution.*"

[14]Employing a neoclassical growth model, it can be shown that the EKC can also result from transitional dynamics.

public policy. We employ the model set up above to investigate the factors which determine this turning point. Unfortunately, closed-form solutions can only be obtained for the centralised economy with $z = 1$. Under these restrictions we can investigate the impact of basic technology and preference parameters on the turning point analytically. This represents an interesting limiting case which is relevant in the sense that the qualitative results largely hold true also for the decentralised economy with $z < 1$. In Section 4.4.3 we turn to the empirically more plausible case of an imperfectly regulated economy with $z < 1$.

First, consider the point in time at which pollution reaches its maximum. From the analytical expression for the time path of pollution [equation (4.28)], one can determine this time threshold (denoted as t^*) to read as follows:

$$t^* = -\frac{\log[K_0^{\alpha+\beta+\upsilon-1}\alpha^{\alpha-1}(\beta+\upsilon)^{\beta+\upsilon}(\alpha+\beta+\upsilon)^{2-\alpha-\beta-\upsilon}\rho^{\alpha+\beta+\upsilon-1}]}{(\alpha+\beta+\upsilon-1)(A-\delta-\rho)}. \quad (4.32)$$

It should be noticed that the desire for a clean environment z, and the parameters reflecting the internal and external effects of consumption on gross pollution (ϕ and ω respectively) do not appear on the RHS, which is due to the restrictions imposed (i.e. $z = 1$ and $\phi + \omega = 1$). Below we will investigate the impact of these parameters numerically. Inserting the preceding expression for the time threshold t^* into the time path of income [$Y(t) = AK(t)$] and using equation (4.26) yields the turning point (denoted as Y^*):[15]

$$Y^* = \frac{A\alpha^{\frac{1-\alpha}{\alpha+\beta+\upsilon-1}}(\beta+\upsilon)^{-\frac{\beta+\upsilon}{\alpha+\beta+\upsilon-1}}(\alpha+\beta+\upsilon)^{1-\frac{1}{\alpha+\beta+\upsilon-1}}}{\rho}. \quad (4.33)$$

This critical income level is determined by the marginal product of capital A, the rate of time preference ρ, the elasticity of consumption in abatement α as well as the elasticities of environmental effort in abatement β and υ. It is independent of the depreciation rate δ and the initial capital stock K_0.

[15]This is basically the solution for the turning point one would obtain from the static Andreoni and Levinson (2001) model.

Table 4.1: Comparative static results for Y^*

	$\frac{\partial Y^*}{\partial x}$ for $x \in \{A, \rho, \alpha, \beta\}$	
A	$Y^* \frac{1}{A}$	> 0
ρ	$Y^* \frac{-1}{\rho}$	< 0
α	$Y^* \frac{(\zeta-1)(-\alpha+\beta+\upsilon)+\alpha\zeta(\log[\zeta]+(\beta+\upsilon)(\log[\beta+\upsilon]-\log[\alpha])}{\alpha\zeta(\zeta-1)^2}$	?
β	$Y^* \frac{2+\zeta(\log[\zeta]-2)+\zeta(\alpha-1)(\log[\alpha]-\log[\beta+\upsilon])}{\zeta(\zeta-1)^2}$	?

From the preceding solution for the turning point (Y^*) we obtain the comparative static results shown in Table 4.1.[16] The first row shows that Y^* increases with the marginal product of capital A. For ease of interpretation, let us assume that $\alpha = \beta + \upsilon$ such that $C = E$.[17] In this case, the level of pollution depends only on consumption. Since an increase in A reduces the consumption rate [equation (4.31)], the required level of income for pollution to reach its maximum increases. The second row indicates that Y^* falls as ρ, i.e. the time preference, rises. An analogous reasoning is applicable here. The rate of consumption rises with ρ [equation (4.31)] and hence the required level of income for pollution to reach its maximum falls. The signs of the partial derivatives of Y^* with respect to the abatement technology parameters α and β are indetermined.[18] In most instances, the derivatives with respect to α and β are negative. An increase in the degree of IRS in abatement leads, ceteris paribus, to a higher abatement output for each level of income and hence to a lower turning point. However, a positive sign can not be excluded in general; for instance, under the restrictions $\alpha = \beta + \upsilon$ and $z = 1$ the derivative with respect to α is positive.[19]

[16] To simplify notation, we define $\zeta = \alpha + \beta + \upsilon$.

[17] A similar reasoning would apply to the case $\alpha \neq \beta + \upsilon$.

[18] Since we are considering the centralised solution with $z = 1$, $\frac{\partial Y^*}{\partial \upsilon} = \frac{\partial Y^*}{\partial \beta}$.

[19] In this case, the relevant range of consumption is $0 < C < 1$. Within this range an

4.4.3 Numerical Analysis

The preceding analysis focused on the centralised solution with $z = 1$ implying that consumption and pollution have the same weight in the utility function. We now investigate the importance of external effects, the effectiveness of public policies and the implications of different environmental preferences. To accomplish this task, the transition process of the model under study must be simulated. We apply the backward integration procedure (e.g. Brunner and Strulik, 2002) to solve for the time paths of the endogenous variables.

Calibration

Table 4.2 shows the baseline set of parameters which underlies the numerical investigations. The time preference rate ρ and the depreciation rate δ are similar to the parameter values used in previous exercises (e.g. Ortigueira and Santos, 1997; Eicher and Turnovsky, 2001). Given these values the marginal product of capital A is chosen such that the implied net rate of return on capital $(A - \delta)$ and the growth rate of per capita income $(A - \delta - \rho)$ are in line with empirically plausible numbers (6% and 2%). The parameter ω determines the strength of the external pollution effect of consumption, while υ captures the external effect of environmental effort in abatement. We choose ω and υ such that the relative external effect of consumption in (gross) pollution $(\frac{\omega}{\phi+\omega})$ and the relative external effect of environmental effort in abatement $(\frac{\upsilon}{\beta+\upsilon})$ are both 10%, implying fairly moderate external effects. As noted above, we assume that the gross pollution function is linear (i.e. $\phi + \omega = 1$).[20]

Turning to the abatement technology parameters (α, β and υ), there are

increase in α lowers, ceteris paribus, the abatement output. As a result, the maximum level of pollution occurs at a higher consumption level. With $\alpha = \beta + \upsilon$ the rate of consumption is independent of α and hence a higher consumption-level implies a higher turning point Y^*.

[20] The alternatives of a concave or convex gross pollution function $G(C)$ appear clearly less plausible.

Table 4.2: Baseline set of parameters

Final output technology	$A = 0.12$; $\delta = 0.06$
Preferences	$\rho = 0.04$
Abatement technology	$\alpha = 0.6$; $\beta = 0.45$; $\upsilon = 0.05$
Gross pollution	$\phi = 0.9$; $\omega = 0.1$

two points to be noticed: First, we assume that there are IRS in abatement, i.e. $\alpha + \beta + \upsilon > 1$. As in Andreoni and Levinson (2001), IRS in abatement are necessary for an EKC. This is in line with Xepapadeas (1994), where IRS in the pollution abatement sector (due to knowledge spillovers) is a necessary condition for unbounded growth without excess pollution (similar results are given in Michel, 1993). Another way to justify IRS in abatement is due to technological progress in the abatement technology (Anderson and Cavendish, 2001). There is also empirical evidence for the existence of IRS in pollution abatement. For instance, Andreoni and Levinson (2001, p. 281) argue that "*at the level of US states, average pollution abatement costs per dollar of GSP [gross state product] decline with industry size, across states and industries, and over time.*" Moreover, Maradan and Vassiliev (2005) report that the marginal opportunity costs of carbon dioxide abatement, measured as forgone production of output, are negatively associated with income. Second, the abatement technology parameters β and υ crucially determine the ratio of abatement expenditures and income. This ratio ranges from about 3% for $z = 0.5$ to 15% for $z = 1$. These values are in line with the empirical figures reported by Brock and Taylor (2004, p. 6).

The turning point

The dependence of the turning point Y^* on the different model parameters is investigated numerically. On this occasion, we consider three different values for the desire for a clean environment z. In addition, the unregulated economy (Table 4.3) is distinguished from an imperfectly regulated economy

(Table 4.4).[21] We focus on these two cases since we believe that the real world is best represented by an unregulated or imperfectly regulated economy. The basic assumption here is that politicians know the optimal taxes but due to imperfections in the political process do not fully implement this optimal tax scheme. The numbers reported in Tables 4.3 and 4.4 show the elasticities of Y^* with respect to different model parameters, i.e. $\frac{\Delta Y^*/Y^*}{\Delta x/x}$ with $x \in \{\omega, \upsilon, A, \rho, \alpha, \beta, z\}$.[22]

Table 4.3: Elasticities of Y^* with respect to model parameters unregulated economy ($\Theta = 0$)

	ω ($\phi + \omega = 1$)	υ	A	ρ	α	β	z
Y^* $z = 1$	0.67	-0.79	0.97	-0.90	-4.41	-5.74	-4.70
Y^* $z = 0.75$	0.46	-1.45	0.98	-0.90	-7.48	-7.40	-4.42
Y^* $z = 0.5$	0.28	-2.22	0.99	-0.91	-9.06	-8.61	-4.19

Three points should be noticed: First, the case of $z = 1$ is qualitatively identical to the cases of $z < 1$. By lowering the desire for a clean environment z, the results change only gradually. Furthermore, the respective elasticities show the same sign for the unregulated economy (Table 4.3) and for the imperfectly regulated economy (Table 4.4). Second, the analytical results from Table 4.1 are confirmed and the ambiguous effects of the abatement

[21]The tax rates imposed are specified as $\tau_C = \Theta_C \tau_C^*$ and $\tau_E = \Theta_E \tau_E^*$, where $\tau_C^* > 0$ and $\tau_E^* < 0$ are optimal taxes (defined in Section 4.3.3); $\Theta_C \geq 0$ and $\Theta_E \geq 0$ indicate the extent of tax implementation. A policy programme which diminishes both market distortions simultaneously is described by $\Theta = \Theta_C = \Theta_E$.

[22]The elasticities are based on an 10% increase of the parameter under consideration.

technology parameters α and β are determined, at least numerically. Third, compared to the case investigated above (centralised solution with $z = 1$) the impact of additional model parameters (i.e. ω and υ) can now be assessed.

The first column of Table 4.3 shows the elasticity of Y^* with respect to ω, i.e. the strength of the external pollution effect of consumption in gross pollution. At the outset, it should be noticed that the restriction for the gross pollution function to be linear ($\phi + \omega = 1$) remains valid, i.e. increasing ω requires a reduction of ϕ. The positive impact of ω on the turning point Y^* can be explained as follows: Since $\phi + \omega$ is held constant, the level of consumption resulting from the centralised solution remains constant. Increasing the external pollution effect of consumption ω leads to a larger gap between the centralised and the decentralised allocation. This implies that decentralised consumption rises, which, holding other things constant, causes a higher level of pollution at each level of income. Graphically speaking, the EKC is expanded outwards and the turning point increases. Moreover, this column also shows that the impact of ω on Y^* increases with the desire for a clean environment z. A higher value of z (i.e. greener preferences) leads to a larger gap between the centralised and the decentralised solution, as can be seen by inspecting the first-order condition (4.18). This implies that the strength of the mechanism described above is reinforced. Finally, the effect of ω on Y^* is smaller for the imperfectly regulated economy (Table 4.4).

The second column of Table 4.3 gives the impact of a variation in the external effect of environmental effort in abatement, υ, on the turning point Y^*, which is negative. An increase in υ has two separate effects: First, environmental effort falls. To understand this effect, consider the case of a variation in υ assuming that $\beta + \upsilon =$ constant. This implies that environmental effort E resulting from the centralised solution remains constant. Since the magnitude of the distortion increases, the gap between the centralised and the decentralised solution gets larger. Hence, E must decrease implying that pollution rises at each level of income and that the turning point increases

Table 4.4: Elasticities of Y^* with respect to model parameters imperfectly regulated economy ($\Theta = 0.5$)

	ω ($\phi + \omega = 1$)	υ	A	ρ	α	β	z
Y^* $z = 1$	0.30	-0.75	0.99	-0.90	-2.71	-4.87	-4.98
Y^* $z = 0.75$	0.21	-1.46	1.00	-0.91	-6.92	-7.00	-4.60
Y^* $z = 0.5$	0.14	-2.27	1.00	-0.91	-8.90	-8.43	-4.29

as well. Second, by holding β fixed (which is assumed in Table 4.3 and 4.4), an increase in υ leads to a higher degree of IRS, which means that pollution at each level of income falls. This implies that the turning point decreases. The second effect dominates the first and hence the sign of this elasticity is negative.[23]

The third column (A) and the fourth column (ρ) are in line with the analytical results obtained from the special case investigated in Section 4.2. The fifth column (α) and sixth (β) column contain negative values. Increasing either α or β increases the degree of IRS in abatement, which has a strong negative impact on the turning point.[24] Finally, the last column (z) shows that an increase in the desire for a clean environment z has a substantially negative impact on the turning point Y^*. This observation is in line with Figure 4.2 below.

[23] The results are nearly identical for the unregulated and the imperfectly regulated economy. This is due to the fact that the IRS argument does not depend on the degree of regulation.

[24] As for the analytical solution the impact of δ is zero.

The effectiveness of public policies

The effectiveness of public policies aimed at a reduction of the environmental burden is investigated. On this occasion, we distinguish between the case of highly environmentally sensitive preferences ($z = 1$) and the case of less environmentally sensitive preferences ($z = 0.5$).

The baseline set of parameters implies fairly moderate external effects, i.e. the relative external effect of consumption in gross pollution ($\frac{\omega}{\phi+\omega}$) and the relative external effect of environmental effort in abatement ($\frac{\upsilon}{\beta+\upsilon}$) are both 10%. Nevertheless, the impact of the associated market failures on the PIR is substantial, as illustrated in Figure 4.2. The PIR labelled "social" shows the EKC resulting from the centralised solution, while the PIR labelled "market" shows the EKC resulting from the unregulated market economy (ignore the curves marked by $\Theta_C = 1$ and $\Theta_E = 1$ for the moment). Moreover, Figure 4.2 (a) is based on $z = 1$, while Figure 4.2 (b) assumes $z = 0.5$. In both cases, the turning point Y^* and the maximum amount of pollution $P^* = P(Y^*)$ are highly sensitive with respect to external effects, i.e. the market economy shows considerably higher values for Y^* and P^* compared to the centralised solution. This implies that public policy should be highly effective with respect to a reduction of the environmental burden.

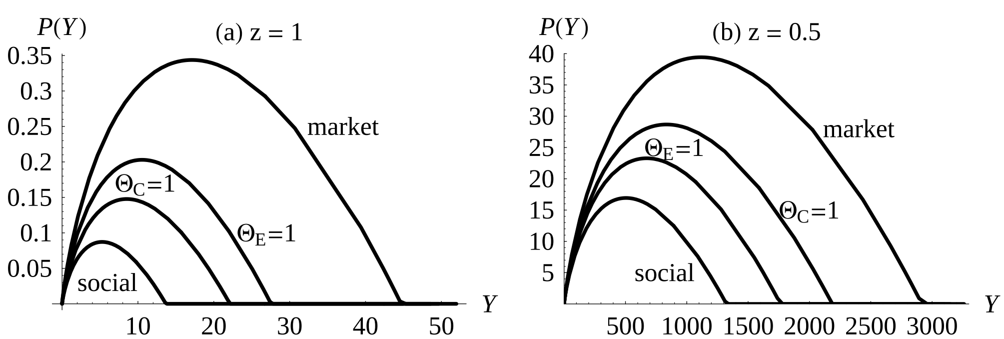


Figure 4.2: Centralised EKC versus decentralised EKC

By imposing appropriate taxes on consumption and subsidies on environmental effort the government can correct the market failures. The taxes imposed are specified as $\tau_C = \Theta_C \tau_C^*$ and $\tau_E = \Theta_E \tau_E^*$, where $\tau_C^* > 0$ and $\tau_E^* < 0$ are optimal taxes (determined in Section 4.3.3) and $\Theta_C \geq 0$ and $\Theta_E \geq 0$ indicate the extent of tax implementation.

Figure 4.2 illustrates the effectiveness of the policy instruments under consideration. The curves labelled as $\Theta_C = 1$ implies that the external effect of polluting consumption is completely internalised, whereas the external effect of environmental effort is not. The curves labelled as $\Theta_E = 1$ shows the reverse situation, i.e. the external effect of environmental effort is completely internalised and the external effect of consumption on gross pollution is not.

We now turn to the relative effectiveness of public policy measures. Figure 4.2 (a) shows that the consumption tax is more effective than a subsidy on environmental effort provided that preferences are extremely environmentally sensitive ($z = 1$). This can be recognised by the fact that the curve $\Theta_C = 1$ lies strictly below the curve $\Theta_E = 1$ implying both a lower turning point Y^* and smaller maximum amount of pollution P^*. In contrast, provided that preferences are less environmentally sensitive ($z = 0.5$) the reverse holds true. A subsidy on environmental effort is more effective than a tax on polluting consumption.

The reason for this observation is as follows: The optimal taxes shown in equations (4.21) and (4.22), which are Pigouvian taxes, indicate the importance of the respective market failure. The optimal environmental effort subsidy is independent of the desire for a clean environment z. It simply corresponds to the share of the external marginal effect of environmental effort to the overall marginal effect of E on pollution. In contrast, the optimal consumption tax depends on z. This can be immediately recognised by inspecting the parameterised versions of τ_C^* and τ_E^*:

$$\tau_C^* = \frac{z\omega C^{\phi+\omega}}{C - z(\phi+\omega)C^{\phi+\omega} + z\alpha C^{\alpha} E^{\beta+\upsilon}} \tag{4.34}$$

$$\tau_E^* = -\frac{\upsilon}{\beta + \upsilon}. \tag{4.35}$$

Holding consumption C and environmental effort E fixed we see that the optimal consumption tax τ_C^* increases with the desire for a clean environment z. For z approaching zero, the representative individual does not care about pollution and hence polluting consumption does not represent a problem. The greener the preferences become (the larger z), the more important is this market failure and the higher the consumption tax should be.[25] For large values of z we find that $|\tau_C^*| > |\tau_E^*|$, which means that the market distortion resulting from polluting consumption is of a higher magnitude than the market distortion associated with environmental effort. Consequently, a consumption tax is more effective than a subsidy on environmental effort. In contrast, provided that z is small enough the reverse holds true, i.e. $|\tau_C^*| < |\tau_E^*|$. In this case, a subsidy on environmental effort is more effective than a consumption tax.

4.5 N-shaped Pollution-Income Relation

There are a number of empirical studies which argue that the PIR is not inverted U-shaped but instead is N-shaped, at least for some pollutants (Grossman and Krueger, 1995, Section IV; Lieb, 2003). This is important because, in this case, pollution eventually increases with income.

The model under study provides a potential explanation for this phenomenon. Imagine the economy develops at first along the upward sloping branch of the EKC resulting from the market economy as shown in Figure 4.3. At some point in time, policy instruments are implemented to internalise external effects and pollution accordingly diminishes. In the model, the economy

[25] This argument is based on holding consumption C and environmental effort E fixed, which is problematic because optimal C and E depend, of course, on z. We checked numerically that $|\tau_C^*| > |\tau_E^*|$ for $z = 1$ and $|\tau_C^*| < |\tau_E^*|$ for $z = 0.5$ indeed holds at each point in time for the simulations underlying Figure 4.2.

jumps to the centralised EKC; of course, in reality this process is distributed over time. Provided that the economy is still below the critical threshold Y^* of the centralised solution, pollution starts to increase again. As a result, one would observe an N-shaped PIR resulting from the interplay of public policy and the intrinsic properties of the model. It should be noticed that this explanation implies in fact an M-shaped PIR. As soon as the peak of pollution (on the centralised EKC) is reached, pollution starts to decline again.

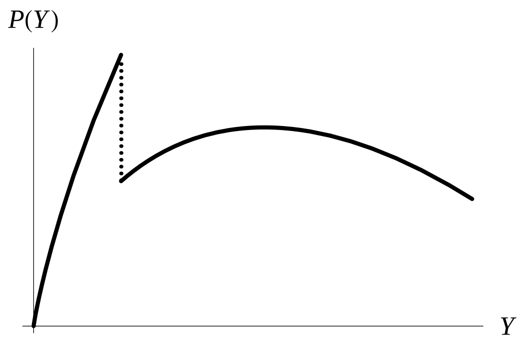


Figure 4.3: M-shaped pollution-income relation

The mechanism sketched above provides one potential explanation for an N-shaped PIR. We do not consider this to be a general explanation. However, future empirical research aimed at explaining this pattern should take this possibility into account. This kind of reasoning implies that the first downward movement is policy induced, i.e. it should succeed the implementation of environmental regulations aimed at a reduction of pollution. The subsequent increase in pollution is then simply due to the fact that growth might be accompanied by a rise in pollution. Moreover, an N-shaped pattern can result provided that there are less than IRS in abatement. Finally, one should notice that Giles and Mosk (2003) find indeed an M-shaped EKC pattern by using long-run data on methane emissions for New Zealand.

4.6 Other Empirical Regularities

A dynamic EKC model should not only be able to reproduce an inverted U-shaped PIR. In addition, it should be compatible with the remaining empirical regularities on economic growth and the environment. These have been reported by Brock and Taylor (2004) based on US data for the period 1950 to 2001: First, the emission intensities (P/Y in our notation) for most pollutants are declining over time. Second, despite the fact that emission intensities decline, the emission levels (P in our notation) continue to increase for a certain period of time. Third, abatement costs relative to GDP (E/Y in our notation) are roughly constant.

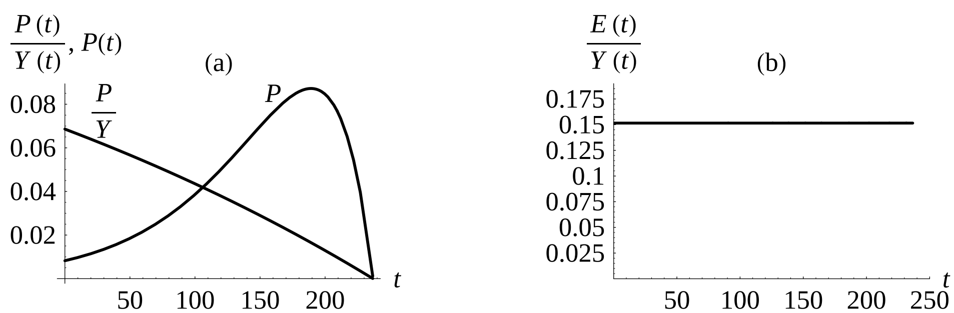


Figure 4.4: Pollution levels, pollution intensity and abatement expenditures

The EKC model set up above is compatible with these empirical regularities. Figure 4.4 (a) shows that the model is in line with the first and the second stylised fact.[26] The emission intensity (P/Y) is indeed declining over time and the pollution level (P) continues to increase for a certain period of time although pollution intensity is falling. Figure 4.4 (b) indicates that the third regularity is also satisfied, i.e. abatement expenditures relative to GDP (E/Y) are indeed constant over time.

In addition, the simple dynamic EKC model (being a standard AK growth model with pollution) is compatible with most of the stylised facts on eco-

[26]Figure 4.4 is based on the centralised solution with $z = 1$ and the baseline set of parameters.

nomic growth, known as the Kaldor (1961) facts: (i) the growth rate of per capita output is constant, (ii) the capital-output ratio is constant and (iii) the real rate of return on capital is constant as well.[27]

4.7 Summary and Conclusions

We have set up a simple dynamic EKC model with multiple market failures resulting from external effects associated with polluting consumption and environmental effort. The model has been used to investigate the determinants of the level of income at which pollution starts to decline (turning point) as well as the relative effectiveness of public policy measures aimed at a reduction of the environmental burden. The main results can be summarised as follows:

(1) The turning point is most strongly affected by the degree of IRS in abatement and the preference for a clean environment. In addition, the magnitude of external effects associated with polluting consumption and environmental effort also has a substantial impact. This aspect points directly to the importance of public policy measures.

(2) Provided that households have a strong preference for a clean environment a consumption tax (i.e. avoiding the problem of pollution) is more effective than a subsidy on environmental effort (i.e. correcting the problem of pollution). In contrast, if households are less environmental sensitive, then a subsidy on environmental effort is more effective in comparison to a consumption tax.

(3) It has been shown that an N-shaped PIR, observable for some specific pollutants, can potentially be explained from the interaction of public policy measures and the intrinsic properties of the model. Although we do not consider this explanation to be valid in general, we think that this kind of reasoning should be taken into account in future empirical research aimed at explaining this pattern.

[27] The model is silent on the constancy of the capital and labour income shares.

(4) In addition to the empirical EKC hypothesis, the dynamic EKC model under study is compatible with the remaining empirical regularities associated with economic growth and the environment. Moreover, the model is also compatible with most of the stylised facts on economic growth due to Kaldor (1961).

Finally, the paper points to a number of interesting questions for future research. For instance, an obvious flaw of the Andreoni and Levinson (2001) model, which becomes especially obvious in a dynamic context, lies in the fact that pollution sooner or later becomes negative as the economy grows provided that there are IRS in abatement. Finding a plausible mechanism which is able to avoid this problematic implication would represent a valuable contribution to the theoretical EKC discussion.

4.8 Appendix

This appendix is compiled using *Mathematica*. Hence, most formulas are in the input- and output style of *Mathematica*. In addition, the variable definitions on pp. XI - XIII do not fully apply.

4.8.1 Concavity Test of the Hamiltonian Functions

Provided that the Hamiltonian is jointly concave in the control and the state variable (Mangasarian sufficiency conditions) or that the maximised Hamiltonian is concave in the state variable (Arrow sufficiency condition), the necessary conditions are also sufficient. Let us focus on the Mangasarian condition.

Conditions for concavity

A twice continuously differentiable function $f(\mathbf{x}) = f(x_1, ..., x_n)$ is concave on an open, convex set S in $\mathbb{R}^n$ if and only if for all $\mathbf{x}$ in S and for all principal minors $\Delta_r(\mathbf{x})$ of the Hessian matrix of f at $\mathbf{x}$, $(-1)^r \Delta_r(\mathbf{x}) \geq 0$ for $r = 1, ..., n$ [Sydsæter et al., 2000 p. 82]. In other words: A function $f(\mathbf{x})$ is concave if its Hessian matrix $\mathcal{H}$ is negative semidefinite. $\mathcal{H}$ is negative semidefinite if its principal minors alternate in sign, beginning with negative. The last principal minor, namely the determinant of $\mathcal{H}$ itself, may be zero. ($\mathcal{H}$ is negative definite if the principal minors alternate in sign and none may be zero [Kamien and Schwartz, 1991 p. 301].)

Example: A general Hamiltonian function

Consider a general Hamiltonian function $H(\cdot)$ with two control variables (c and e), one state variable (k) and one co-state variable (λ): $H[c, e, k, \lambda]$. The Hessian matrix $\mathcal{H}$ is then given by:

$$\mathcal{H} = \begin{pmatrix} H_{cc} & H_{ce} & H_{ck} \\ H_{ec} & H_{ee} & H_{ek} \\ H_{kc} & H_{ke} & H_{kk} \end{pmatrix}$$

For concavity of the Hamiltonian H the following three conditions must be satisfied:

(1) $H_{cc} \leq 0$

(2) $H_{cc}H_{ee} - H_{ce}H_{ec} \geq 0$

(3) $\det H \leq 0$

Concavity of the Hamiltonian for the centralised solution

Inserting the parameterised instantaneous utility, gross pollution and abatement functions [equations (4.23) to (4.25) of the main text] into the Hamiltonian function for the centralised solution [equation (4.17) of the main text] yields:

$$\mathbf{H = u[c, p] + \boldsymbol{\lambda}(f[k] - \boldsymbol{\delta} k - c - e)};$$

$$\mathbf{u[c\_, p\_] = log[c - zp]};$$

$$\mathbf{p = c - c^{\boldsymbol{\alpha}} e^{\boldsymbol{\beta}+\boldsymbol{\eta}}};$$

$$\mathbf{f[k] = Ak};$$

$$\mathbf{H}$$

$$(-\mathrm{c} - \mathrm{e} + \mathrm{Ak} - \mathrm{k}\delta)\lambda + \mathrm{Log}\left[\mathrm{c} - \left(\mathrm{c} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}\right]$$

The Hessian matrix $\mathcal{H}$ is given by:

$$\begin{aligned}\boldsymbol{\mathcal{H}} = &\mathbf{\{\{D[H, \{c, 2\}], D[H, c, e], D[H, c, k]\},}\\ &\mathbf{\{D[H, e, c], D[H, \{e, 2\}], D[H, e, k]\},}\\ &\mathbf{\{D[H, k, c], D[H, k, e], D[H, \{k, 2\}]\}\}}\end{aligned}$$

$$\begin{aligned}&\left\{\left\{\frac{\mathrm{c}^{-2+\alpha}\mathrm{e}^{\beta+\eta}\mathrm{z}(-1+\alpha)\alpha}{\mathrm{c} - \left(\mathrm{c} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}} - \frac{\left(1 - \mathrm{z}\left(1 - \mathrm{c}^{-1+\alpha}\mathrm{e}^{\beta+\eta}\alpha\right)\right)^2}{\left(\mathrm{c} - \left(\mathrm{c} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}\right)^2},\right.\right.\\
&\left.\frac{\mathrm{c}^{-1+\alpha}\mathrm{e}^{-1+\beta+\eta}\mathrm{z}\alpha(\beta+\eta)}{\mathrm{c} - \left(\mathrm{c} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}} - \frac{\mathrm{c}^{\alpha}\mathrm{e}^{-1+\beta+\eta}\mathrm{z}\left(1 - \mathrm{z}\left(1 - \mathrm{c}^{-1+\alpha}\mathrm{e}^{\beta+\eta}\alpha\right)\right)(\beta+\eta)}{\left(\mathrm{c} - \left(\mathrm{c} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}\right)^2}, 0\right\},\\
&\left\{\frac{\mathrm{c}^{-1+\alpha}\mathrm{e}^{-1+\beta+\eta}\mathrm{z}\alpha(\beta+\eta)}{\mathrm{c} - \left(\mathrm{c} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}} - \frac{\mathrm{c}^{\alpha}\mathrm{e}^{-1+\beta+\eta}\mathrm{z}\left(1 - \mathrm{z}\left(1 - \mathrm{c}^{-1+\alpha}\mathrm{e}^{\beta+\eta}\alpha\right)\right)(\beta+\eta)}{\left(\mathrm{c} - \left(\mathrm{c} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}\right)^2},\right.\\
&\left.\left.\frac{\mathrm{c}^{\alpha}\mathrm{e}^{-2+\beta+\eta}\mathrm{z}(-1+\beta+\eta)(\beta+\eta)}{\mathrm{c} - \left(\mathrm{c} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}} - \frac{\mathrm{c}^{2\alpha}\mathrm{e}^{-2+2\beta+2\eta}\mathrm{z}^2(\beta+\eta)^2}{\left(\mathrm{c} - \left(\mathrm{c} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}\right)^2}, 0\right\}, \{0, 0, 0\}\right\}\end{aligned}$$

Condition (3) (see above) is easily satisfied, since all cross derivatives with respect to k are zero.

Simplify[Det[$\mathcal{H}$] $\leq$ 0]

True

Condition (1) is satisfied too. Consider H_{cc}

Minors[$\mathcal{H}$, 1][[1, 1]]

$$\frac{\mathrm{c}^{-2+\alpha}\mathrm{e}^{\beta+\eta}\mathrm{z}(-1+\alpha)\alpha}{\mathrm{c}-\left(\mathrm{c}-\mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}}-\frac{\left(1-\mathrm{z}\left(1-\mathrm{c}^{-1+\alpha}\mathrm{e}^{\beta+\eta}\alpha\right)\right)^{2}}{\left(\mathrm{c}-\left(\mathrm{c}-\mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}\right)^{2}}$$

This expression is unambiguously negative. Given our assumption $P \geq 0$ and the parameter restrictions, the numerator of the first term is negative, whereas the denominator is positive. Thus the first term is negative. Both the numerator and the denominator of the second term are positive. Subtracting the second term from the first, yields a negative expression.

It remains to investigate condition (2), i.e. $H_{cc}H_{ee} - H_{ce}H_{ec} \geq 0$. As we have shown H_{cc} is negative. H_{ee} is negative as long as $\beta + \eta < 1$. Otherwise, H_{ee} could be positive as well. $H_{ce}H_{ec}$ is certainly positive, since $H_{ce} = H_{ec}$ (Young's theorem). Thus, the sign of the second principal minor depends on (i) the sign of $\beta + \eta$ and (ii) the absolute values of $H_{cc}H_{ee}$ and $H_{ce}H_{ec}$. For condition (2) to be satisfied $|H_{cc}H_{ee}| \geq |H_{ce}H_{ec}|$ and $\beta + \eta < 1$ must hold.

$\mathbf{H_{ee}}$ = D[H, {e, 2}]

$$\frac{\mathrm{c}^{\alpha}\mathrm{e}^{-2+\beta+\eta}\mathrm{z}(-1+\beta+\eta)(\beta+\eta)}{\mathrm{c}-\left(\mathrm{c}-\mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}}-\frac{\mathrm{c}^{2\alpha}\mathrm{e}^{-2+2\beta+2\eta}\mathrm{z}^{2}(\beta+\eta)^{2}}{\left(\mathrm{c}-\left(\mathrm{c}-\mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right)\mathrm{z}\right)^{2}}$$

Unfortunately, $|H_{cc}H_{ee}| \geq |H_{ce}H_{ec}|$ can not be answered analytically. Thus, we check condition (2) numerically. Specifically, we determine the sign of the second principal minor using the baseline set of parameters (Table 4.2 of the main text) for the different values of z used in Section 4.4.3 of the main text, i.e. $z = 1$, $z = 0.75$ and $z = 0.5$.

The baseline set of parameters is given by:

$$\boldsymbol{\alpha} = \frac{\mathbf{6}}{\mathbf{10}}; \boldsymbol{\beta} = \frac{\mathbf{45}}{\mathbf{100}}; \boldsymbol{\eta} = \frac{\mathbf{5}}{\mathbf{100}}; \boldsymbol{\phi} = \frac{\mathbf{9}}{\mathbf{10}}; \boldsymbol{\omega} = \frac{\mathbf{1}}{\mathbf{10}}; \boldsymbol{\rho} = \frac{\mathbf{4}}{\mathbf{100}}; \boldsymbol{\delta} = \frac{\mathbf{6}}{\mathbf{100}}; \mathbf{A} = \frac{\mathbf{12}}{\mathbf{100}};$$

1. Case: $z = 1$

   $\mathbf{z = 1}$;

   $\mathbf{Simplify}[\mathbf{Minors}[\boldsymbol{\mathcal{H}}, \mathbf{2}][[\mathbf{1}, \mathbf{1}]] \geq \mathbf{0}, \{\mathbf{c} > \mathbf{0}, \mathbf{e} > \mathbf{0}\}]$

   True

2. Case: $z = 0.75$

   $\mathbf{z = 0.75}$;

   $\mathbf{Simplify}[\mathbf{Minors}[\boldsymbol{\mathcal{H}}, \mathbf{2}][[\mathbf{1}, \mathbf{1}]] \geq \mathbf{0}, \{\mathbf{c} > \mathbf{0}, \mathbf{e} > \mathbf{0}\}]$

   True

3. Case: $z = 0.5$

   $\mathbf{z = 0.5}$;

   $\mathbf{Simplify}[\mathbf{Minors}[\boldsymbol{\mathcal{H}}, \mathbf{2}][[\mathbf{1}, \mathbf{1}]] \geq \mathbf{0}, \{\mathbf{c} > \mathbf{0}, \mathbf{e} > \mathbf{0}\}]$

   True

All three conditions for concavity of H are satisfied. Therefore, the Hamiltonian for the centralised solution is indeed concave (at least for the baseline set of parameters).

Simplified Hamiltonian $z = 1$

For the special case $z = 1$, the Hamiltonian (for the centralised solution) simplifies and the question of concavity can be answered in general.

$\mathbf{Clear}[\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\eta}, \boldsymbol{\phi}, \boldsymbol{\omega}, \boldsymbol{\rho}, \boldsymbol{\delta}, \mathbf{A}]$

$\mathbf{z = 1}$;

$\bar{\mathbf{H}} = \mathbf{H}$

$(-\mathrm{c} - \mathrm{e} + \mathrm{Ak} - \mathrm{k}\delta)\lambda + \log\left[\mathrm{c}^{\alpha}\mathrm{e}^{\beta+\eta}\right]$

The Hessian matrix $\bar{\mathcal{H}}$is now given by:

$$\boldsymbol{\bar{\mathcal{H}}} = \{\{\mathbf{D}[\bar{\mathbf{H}},\{\mathbf{c},\mathbf{2}\}],\mathbf{D}[\bar{\mathbf{H}},\mathbf{c},\mathbf{e}],\mathbf{D}[\bar{\mathbf{H}},\mathbf{c},\mathbf{k}]\},\{\mathbf{D}[\bar{\mathbf{H}},\mathbf{e},\mathbf{c}],\mathbf{D}[\bar{\mathbf{H}},\{\mathbf{e},\mathbf{2}\}],$$
$$\mathbf{D}[\bar{\mathbf{H}},\mathbf{e},\mathbf{k}]\},\{\mathbf{D}[\bar{\mathbf{H}},\mathbf{k},\mathbf{c}],\mathbf{D}[\bar{\mathbf{H}},\mathbf{k},\mathbf{e}],\mathbf{D}[\bar{\mathbf{H}},\{\mathbf{k},\mathbf{2}\}]\}\};$$

$$\overline{\boldsymbol{\mathcal{H}}\mathbf{1}} = \boldsymbol{\bar{\mathcal{H}}}//\mathbf{MatrixForm}$$

$$\begin{pmatrix} -\frac{\alpha}{c^2} & 0 & 0 \\ 0 & -\frac{\beta+\eta}{e^2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

The same three conditions as above must be satisfied.
Condition (1):

$$\mathbf{Minors}[\boldsymbol{\bar{\mathcal{H}}},\mathbf{1}][[\mathbf{1},\mathbf{1}]]$$

$$\mathbf{Simplify}[\mathbf{Minors}[\boldsymbol{\bar{\mathcal{H}}},\mathbf{1}][[\mathbf{1},\mathbf{1}]] \leq \mathbf{0},$$
$$\{\mathbf{c} > \mathbf{0},\mathbf{e} > \mathbf{0},\mathbf{0} < \boldsymbol{\alpha} < \mathbf{1},\mathbf{0} < \boldsymbol{\beta} < \mathbf{1},\mathbf{0} < \boldsymbol{\eta} < \mathbf{1}\}]$$

$$-\frac{\alpha}{\mathrm{c}^2}$$

True

Condition (2):

$$\mathbf{Minors}[\boldsymbol{\bar{\mathcal{H}}},\mathbf{2}][[\mathbf{1},\mathbf{1}]]$$

$$\mathbf{Simplify}[\mathbf{Minors}[\boldsymbol{\bar{\mathcal{H}}},\mathbf{2}][[\mathbf{1},\mathbf{1}]] \geq \mathbf{0},$$
$$\{\mathbf{c} > \mathbf{0},\mathbf{e} > \mathbf{0},\mathbf{0} < \boldsymbol{\alpha} < \mathbf{1},\mathbf{0} < \boldsymbol{\beta} < \mathbf{1},\mathbf{0} < \boldsymbol{\eta} < \mathbf{1}\}]$$

$$\frac{\alpha(\beta+\eta)}{\mathrm{c}^2\mathrm{e}^2}$$

True

Condition (3):

$$\mathbf{Det}[\boldsymbol{\bar{\mathcal{H}}}]$$

$$\mathbf{Simplify}[\mathbf{Det}[\boldsymbol{\bar{\mathcal{H}}}] \leq \mathbf{0}]$$

0

True

Concavity of the Hamiltonian for the decentralised solution

Inserting the parameterised instantaneous utility, gross pollution and abatement functions [equations (4.23) to (4.25) of the main text] into the Hamiltonian function for the centralised solution [equation (4.9) of the main text] yields ($cc = \bar{c}$ and $ee = \bar{e}$):

$$\mathbf{Clear[H, u, p, \lambda, r, k, \tau_c, \tau_e, f, z, \alpha, \beta, \eta, \phi, \omega, \rho, \delta, A, c, e, ee, cc]}$$

$$\mathbf{H = u[c, p] + \lambda(rk - (1 + \tau_c)c - (1 + \tau_e)e + T);}$$

$$\mathbf{u[c\_, p\_] = log[c - zp];}$$

$$\mathbf{p = c^{\phi}cc^{\omega} - c^{\alpha}e^{\beta}ee^{\eta};}$$

$$\mathbf{f[k] = Ak;}$$

$$\mathbf{H}$$

$$\lambda(\mathrm{kr} + \mathrm{T} - \mathrm{c}(1 + \tau_{\mathrm{c}}) - \mathrm{e}(1 + \tau_{\mathrm{e}})) + \log[\mathrm{c} - (\mathrm{c}^{\phi}\mathrm{cc}^{\omega} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta})\mathrm{z}]$$

The Hessian matrix $\mathcal{H}$ is given by:

$$\begin{aligned}\mathcal{H} = &\mathbf{\{\{D[H, \{c, 2\}], D[H, c, e], D[H, c, k]\},}\\ &\mathbf{\{D[H, e, c], D[H, \{e, 2\}], D[H, e, k]\},}\\ &\mathbf{\{D[H, k, c], D[H, k, e], D[H, \{k, 2\}]\}\}}\end{aligned}$$

$$\Bigg\{\Bigg\{-\frac{\mathrm{z}\left(-\mathrm{c}^{-2+\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}(-1+\alpha)\alpha + \mathrm{c}^{-2+\phi}\mathrm{cc}^{\omega}(-1+\phi)\phi\right)}{\mathrm{c} - \left(\mathrm{c}^{\phi}\mathrm{cc}^{\omega} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}\right)\mathrm{z}} - \frac{\left(1 - \mathrm{z}\left(-\mathrm{c}^{-1+\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}\alpha + \mathrm{c}^{-1+\phi}\mathrm{cc}^{\omega}\phi\right)\right)^2}{\left(\mathrm{c} - \left(\mathrm{c}^{\phi}\mathrm{cc}^{\omega} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}\right)\mathrm{z}\right)^2}, \frac{\mathrm{c}^{-1+\alpha}\mathrm{e}^{-1+\beta}\mathrm{ee}^{\eta}\mathrm{z}\alpha\beta}{\mathrm{c} - \left(\mathrm{c}^{\phi}\mathrm{cc}^{\omega} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}\right)\mathrm{z}} - \frac{\mathrm{c}^{\alpha}\mathrm{e}^{-1+\beta}\mathrm{ee}^{\eta}\mathrm{z}\beta\left(1 - \mathrm{z}\left(-\mathrm{c}^{-1+\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}\alpha + \mathrm{c}^{-1+\phi}\mathrm{cc}^{\omega}\phi\right)\right)}{\left(\mathrm{c} - \left(\mathrm{c}^{\phi}\mathrm{cc}^{\omega} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}\right)\mathrm{z}\right)^2}, 0\Bigg\},$$

$$\Bigg\{\frac{\mathrm{c}^{-1+\alpha}\mathrm{e}^{-1+\beta}\mathrm{ee}^{\eta}\mathrm{z}\alpha\beta}{\mathrm{c} - \left(\mathrm{c}^{\phi}\mathrm{cc}^{\omega} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}\right)\mathrm{z}} - \frac{\mathrm{c}^{\alpha}\mathrm{e}^{-1+\beta}\mathrm{ee}^{\eta}\mathrm{z}\beta\left(1 - \mathrm{z}\left(-\mathrm{c}^{-1+\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}\alpha + \mathrm{c}^{-1+\phi}\mathrm{cc}^{\omega}\phi\right)\right)}{\left(\mathrm{c} - \left(\mathrm{c}^{\phi}\mathrm{cc}^{\omega} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}\right)\mathrm{z}\right)^2}, \frac{\mathrm{c}^{\alpha}\mathrm{e}^{-2+\beta}\mathrm{ee}^{\eta}\mathrm{z}(-1+\beta)\beta}{\mathrm{c} - \left(\mathrm{c}^{\phi}\mathrm{cc}^{\omega} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}\right)\mathrm{z}} - \frac{\mathrm{c}^{2\alpha}\mathrm{e}^{-2+2\beta}\mathrm{ee}^{2\eta}\mathrm{z}^2\beta^2}{\left(\mathrm{c} - \left(\mathrm{c}^{\phi}\mathrm{cc}^{\omega} - \mathrm{c}^{\alpha}\mathrm{e}^{\beta}\mathrm{ee}^{\eta}\right)\mathrm{z}\right)^2}, 0\Bigg\}, \{0, 0, 0\}\Bigg\}$$

Again, conditions (1) to (3) must be satisfied (see above). Condition (3) is again satisfied, since all cross derivatives with respect to k are zero.

$\mathbf{Simplify[Det[\mathcal{H}] \leq 0]}$

True

The sign of the first and second principal minor of $\mathcal{H}$ [conditions (1) and (2)] can not be determined analytically. Thus we check conditions (1) and (2) numerically. Specifically, we determine the sign of the first and the second principal minor of $\mathcal{H}$ using the baseline set of parameters (Table 4.2 of the main text) for the different values of z used in Section 4.4.3 of the main text, i.e. $z = 1$, $z = 0.75$ and$z = 0.5$. The taxes have no influence on the concavity of the Hamiltonian (τc, τe do not appear in the Hessian matrix). Since we have a large number of identical households ordered on the interval [0,1], we can set $\bar{c} = c$ and $\bar{e} = e$ (here: $cc = c$, $ee = e$) after having determined the derivatives.

The baseline set of parameters is given by:

$$\boldsymbol{\alpha} = \frac{\mathbf{6}}{\mathbf{10}}; \boldsymbol{\beta} = \frac{\mathbf{45}}{\mathbf{100}}; \boldsymbol{\eta} = \frac{\mathbf{5}}{\mathbf{100}}; \boldsymbol{\phi} = \frac{\mathbf{9}}{\mathbf{10}}; \boldsymbol{\omega} = \frac{\mathbf{1}}{\mathbf{10}}; \boldsymbol{\rho} = \frac{\mathbf{4}}{\mathbf{100}}; \boldsymbol{\delta} = \frac{\mathbf{6}}{\mathbf{100}};$$
$$\mathbf{A} = \frac{\mathbf{12}}{\mathbf{100}}; \mathbf{cc} = \mathbf{c}; \mathbf{ee} = \mathbf{e};$$

1. Case: z=1

$\mathbf{z = 1};$

$\mathbf{Simplify[Minors[\mathcal{H}, 1][[1, 1]] \leq 0, \{c > 0, e > 0\}]}$

$\mathbf{Simplify[Minors[\mathcal{H}, 2][[1, 1]] \geq 0, \{c > 0, e > 0\}]}$

True

True

2. Case: z=0.75

$\mathbf{z = 0.75}$;

$\mathbf{Simplify[Minors[\boldsymbol{\mathcal{H}}, 1][[1, 1]] \leq 0, \{c > 0, e > 0\}]}$

$\mathbf{Simplify[Minors[\boldsymbol{\mathcal{H}}, 2][[1, 1]] \geq 0, \{c > 0, e > 0\}]}$

True

True

3. Case: z=0.5

$\mathbf{z = 0.5}$;

$\mathbf{Simplify[Minors[\boldsymbol{\mathcal{H}}, 1][[1, 1]] \leq 0, \{c > 0, e > 0\}]}$

$\mathbf{Simplify[Minors[\boldsymbol{\mathcal{H}}, 2][[1, 1]] \geq 0, \{c > 0, e > 0\}]}$

True

True

Thus, all three conditions for concavity of H are satisfied. Therefore, the Hamiltonian for the decentralised solution is indeed concave (at least for the baseline set of parameters).

Perturbations of the baseline set of parameters

We checked concavity of the Hamiltonian for perturbations of the baseline set of parameters. For instance, consider the following two examples for $z = 0.75$. In the first example we increased α by 10 per cent. In the second we increased all parameters by 10 per cent (with the exception of ϕ and ω in order to retain a linear gross pollution function).

1. Example:

$$\boldsymbol{\alpha = \frac{66}{100}; \beta = \frac{45}{100}; \eta = \frac{5}{100}; \phi = \frac{9}{10}; \omega = \frac{1}{10}; \rho = \frac{4}{100}; \delta = \frac{6}{100};}$$
$$\mathbf{A = \frac{12}{100}; cc = c; ee = e; z = 0.75;}$$

$\mathbf{Simplify[Minors[\mathcal{H}, 1][[1, 1]] \leq 0, \{c > 0, e > 0\}]}$

$\mathbf{Simplify[Minors[\mathcal{H}, 2][[1, 1]] \geq 0, \{c > 0, e > 0\}]}$

$\mathbf{Simplify[Det[\mathcal{H}] \leq 0]}$

True

True

True

2. Example:

$$\boldsymbol{\alpha = \frac{66}{100}; \beta = \frac{495}{1000}; \eta = \frac{55}{1000}; \phi = \frac{9}{10}; \omega = \frac{1}{10}; \rho = \frac{44}{1000}; \delta = \frac{66}{1000};}$$
$$\mathbf{A = \frac{132}{1000}; cc = c; ee = e; z = 0.75;}$$

$\mathbf{Simplify[Minors[\mathcal{H}, 1][[1, 1]] \leq 0, \{c > 0, e > 0\}]}$

$\mathbf{Simplify[Minors[\mathcal{H}, 2][[1, 1]] \geq 0, \{c > 0, e > 0\}]}$

$\mathbf{Simplify[Det[\mathcal{H}] \leq 0]}$

True

True

True

Chapter 5

A New Approach to Pollution Modelling in Models of the Environmental Kuznets Curve*

Models of the Environmental Kuznets Curve, particularly those with an explicit abatement technology, often involve that pollution becomes negative in the long run. This, of course, is a highly implausible prediction. The paper at hand examines the problem of negative pollution by, first, critically discussing two approaches adopted in existing EKC models and, second, by proposing a new approach. Motivated by the debatable assumption of perpetually increasing returns to scale in abatement, the idea of fading increasing returns to scale is introduced. This procedure does not only constitute a solution to the theoretical problem of negative pollution, but also does well regarding the empirical plausibility of the abatement technology.

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5.1 Introduction

Knowledge about the relationship between environmental pollution and income is decisive for reliable predictions of long-term development of individual welfare. If the pollution-income relation is characterised by the eventual decoupling of pollution from economic growth, then sustained growth without excess pollution could be feasible. If, on the other hand, economic growth invariably comes with increasing environmental degradation, the growth potential could be limited, as propagated by the Club of Rome (Meadows et al., 1972).

The Environmental Kuznets Curve (EKC) is one of the most-used concepts to analyse the pollution-income relation. EKC models largely dominate both the empirical and theoretical literature on economic growth and pollution. The theoretical literature on EKCs can be separated into two major strands. The first class of models stresses shifts in the production technologies, which differ in their pollution intensity, as the main cause for the hump-shaped pollution-income relation. Prominent examples of this strand are the contribution of Stokey (1998) and the model of Chapter 3. In the second class, the inverted U-shaped pollution-income relation results from the explicitly modelled abatement of (gross) pollution. That is, besides consumption and investments in accumulable (human or physical) capital, there is an additional economic activity, namely environmental effort. The characteristics of the abatement technology are crucial for the occurrence of an EKC. Examples for this strand of EKC models are John and Pecchenino (1994), Selden and Song (1995), Andreoni and Levinson (2001), Brock and Taylor (2004) and the model analysed in Chapter 4.[1]

The focus of this paper lies on EKC models of the second class and, in

[1] De Groot (1999) stresses structural changes within an economy as the main cause for an EKC. However, the underlying mechanism is largely restricted to developing countries and does not apply in the same way to mature economies. As a result, this mechanism has not attracted considerable attention in the EKC literature.

particular, on models where net pollution is defined as the difference between gross pollution and abatement. The main characteristic necessary to generate an EKC is a form of increasing returns to scale (IRS) in the abatement technology (see Andreoni and Levinson, 2001). But assuming IRS in abatement only leads to reasonable implications in the short and medium run. In the long run, this specific model set-up often results in unrealistic implications. Pollution both as a stock and as a flow variable can become negative as soon as the whole stock of pollution – if there is any at all – has been abated and the actual output of the "abatement sector", i.e. abated pollution, is greater than the amount of pollution generated by the polluting activities. This, of course, is an incorrect prediction. In order to diminish environmental degradation, there must be a positive amount of pollution in the first place – at least from a logical point of view. As a result, negative net pollution flows can only be justified as long as there is a positive pollution stock. It should be noted that the problem of negative pollution arises with or without the incorporation of a pollution stock. In the former case, the problem is less severe since temporarily negative pollution flows can be justified and typically arises at a later date.

The potential occurrence of negative pollution is, however, not only a technical problem, which could be solved by appropriate constraints, but has severe consequences. Specifically, even the reliability of the predictions for the short and medium run are challenged. If a model implies implausible or incorrect predictions for the long run, the model specification does apparently not reflect real economic relations or the facts observed by the natural sciences.

Up to now, the problem of negative pollution has not been adequately addressed in the theoretical EKC literature. Therefore, the hitherto existing predictions might not be optimal or reliable. The present paper tries to close this gap. In a first step, it critically discusses two approaches to avoiding negative pollution, which are adopted in existing EKC models. These are, first, the restriction to interior solutions, i.e. only that period of time or development phase is considered where pollution is positive. Second, the original modelling with net pollution as the difference between gross pollution and abatement is converted into a specification in line with pollution intensities. Since intensities are non-negative by definition, pollution will be non-negative as well. In a second step, a new approach for modelling pollution in EKC models with abatement is introduced. It is argued that the assumption of perpetual increasing returns to scale in abatement is debatable. In consequence, the main mechanism of the proposed approach lies in a continuous restraint of the degree of the IRS in the abatement sector. With an appropriate functional specification of the model, pollution stocks and flows remain strictly positive.

The remainder of this paper is organised as follows. The first step, i.e. the discussion of the existing approaches to avoid negative pollution, is dealt with in Sections 5.2 (restriction to interior solutions) and 5.3 (conversion of the pollution function with explicit gross pollution and abatement functions into a specification with a pollution intensity). The subsequent two sections address the second step. In Section 5.4, the evidence on economies of scale in abatement is discussed. Section 5.5 deals with the new approach of fading increasing returns to scale in abatement. Finally, Section 5.6 concludes.

5.2 Interior Solutions and Non-Negativity Constraint

In most theoretical EKC models, the hump-shaped pollution-income relation occurs at early stages of economic development. That is, pollution rises right from the start, until eventually a decoupling of environmental degradation from economic growth occurs. The problem of negative pollution – as a flow or as a stock variable – emerges relatively late in the development process, after abatement has succeeded in reducing pollution to zero. On account of this chronology, some models ignore the possibility of negative pollution and make do with the proof of an inverted U-shaped pollution-income relation or turn the attention to interior solutions only (e.g. Selden and Song, 1995). By disregarding the eventuality of negative pollution and the associated unrealistic implications, these procedures are not fully satisfying despite their simplicity and manageability.

The first approach to avoiding negative pollution is a purely technical solution. Specifically, the model under consideration is augmented by a non-negativity constraint for pollution. As an illustration, consider the following net pollution function known from literature:[2]

$$P(C, E) = \Lambda[C - B(C, E)], \tag{5.1}$$

where P is net pollution, C consumption, E environmental effort, Λ a pollution intensity parameter reflecting the actual state of the technological knowledge and $B(\cdot)$ is the abatement technology. Gross pollution, reflected by the first term in brackets, is a linear function of the polluting economic activity, namely consumption.[3] Andreoni and Levinson (2001) show that with a linear gross pollution function, increasing returns to scale in abatement is a necessary condition for an EKC pattern. The non-negativity constraint for pollution then requires:

$$P(C, E) \geq 0. \tag{5.2}$$

Provided that both C and E grow over time and that abatement is characterised by IRS, net pollution [equation (5.1)] would eventually become negative. Hence, equation (5.2) becomes binding sooner or later. In order to satisfy the non-negativity constraint, consumption and environmental effort can no longer be chosen independently. In fact, for $P = 0$ environmental effort is no longer an independent choice variable but rather a function of consumption.

[2]To simplify notation, the time index is suppressed.

[3]More frequently, pollution is modelled as a by-product of production (e.g. Xepapadeas, 2004). However, the assumption that only part of the production is polluting is warrantable as well (John and Pecchenino, 1994).

The consideration of a non-negativity constraint for pollution does not constitute a satisfying solution for the problem of negative pollution. The prevention of negative pollution is of a solely technical nature and not due to a more realistic abatement function. Thus, the reservations about pollution functions implying negative pollution in the long run still apply. Moreover, both consumption and environmental effort are discontinuous at the point in time where the non-negativity constraint becomes binding. The empirical plausibility of such discontinuities is questionable.

5.3 From Abatement to Pollution Intensities

Since the potential occurrence of negative pollution can be traced back inter alia to the modelling of net pollution as the difference between gross pollution and abatement, the second approach to avoiding negative pollution starts at this point. Specifically, the idea is to convert the original specification with explicit gross pollution and abatement functions into a specification, where net pollution is given by the product of the polluting economic activity and a measurement for environmental effort (see e.g. the *Green Solow Model* of Brock and Taylor, 2004). One could argue that this procedure, i.e. the pooling of the gross pollution and abatement functions, corresponds to a specification characterised by pollution intensities. In other words, the mechanism employed by the other prevailing class of theoretical EKC models (see Section 5.1) is adopted.

For an illustration of this procedure, consider the same net pollution function as in Section 5.2 [equation (5.1)]. Assuming – as Brock and Taylor (2004) – that $B(\cdot)$ is linearly homogeneous and defining $h = \frac{E}{C}$, the pollution function can be rewritten as:

$$P(C, E) = \Lambda C[1 - B(1, h)], \tag{5.3}$$

respectively as:

$$P = \Lambda C b(h) \qquad \text{where} \quad b(h) = [1 - B(1, h)], \tag{5.4}$$

where $b(h)$ can be regarded as an abatement function in intensive form depending on the ratio of (polluting) consumption and environmental effort. However, rewriting equation (5.1) with a pollution intensity term is not a remedy for negative pollution. The success of this approach lies rather in the adequate choice of the functional form of the abatement function in intensive form. For plausibility reasons, environmental effort should have a positive but decreasing marginal effect on pollution reduction, i.e. the following conditions should hold: $b(0) = 1$, $b'(h) < 0$ and $b''(h) > 0$. To prevent pollution from becoming negative, $b(h)$ must additionally satisfy

$$\lim_{h \to \infty} b(h) \geq 0. \tag{5.5}$$

Otherwise, the non-negativity of pollution is not guaranteed. Provided that $C > E$ and, hence, $0 \leq h \leq 1$ the following functional form could be employed:

$$b(h) = (1 - h)^{\epsilon} \qquad \text{with} \quad \epsilon > 1 \tag{5.6}$$

This function has the desired attributes and satisfies the condition for non-negative pollution.[4] Even if the same amount were be spent for abatement as for consumption, pollution would simply be equal to zero but never become negative. However, if h were constant or bounded from above with an upper bound smaller than unity, there would have to be technological progress targeted at more environmentally friendly production technologies (thereby reducing the intensity parameter Λ) in order to get a pollution-income relation in line with the EKC.

At first glance, the procedure outlined in this section seems to be a solution to avoid negative pollution. At closer inspection, however, it becomes clear that its success depends on the accurate specification of the abatement function in intensive form $[b(h)]$. In addition, technological progress could possibly be necessary for an EKC-type pollution-income relation.

[4]Equation (5.6) is adopted from Brock and Taylor (2004). In their model, production and not only consumption is polluting. Hence, h is defined as the fraction of overall economic activity dedicated to abatement and $0 \leq h \leq 1$ is fulfilled by definition.

5.4 Evidence on Returns in Abatement

As pointed out in Section 5.1, many EKC models are based on a form of scale economies, which can be due to direct modelling or due to fixed costs.[5] By explicitly modelling an abatement technology, Andreoni and Levinson (2001) demonstrate that IRS in abatement are crucial for the occurrence of an EKC pattern. This applies provided that the gross pollution function is linear. In a more general version of the Andreoni and Levinson (2001) model, Plassmann and Khanna (2004, p. 16) show that "*for non-constant returns to scale in gross pollution, a sufficient condition for pollution to decline is rather that the returns to scale in abatement exceed the returns to scale in gross pollution.*" Formally, assume that the abatement function $B(C, E)$ is homogeneous of degree d and the gross pollution function $G(C)$ is homogeneous of degree νd. Then, a sufficient condition of an EKC pattern is $\nu < 1$.[6]

However, if pollution is considered in terms of emissions – as opposed to in terms of ambient concentration or in terms of damage – the assumption of a linear gross pollution function is most appropriate. In this paper, the focus lies on pollution as a flow variable and, hence, pollution should be best regarded in terms of emissions. Thus, the leading cause for the occurrence of negative pollution is the assumption of IRS in abatement. On this occasion, the question of the plausibility of increasing returns to scale in abatement arises. Is the pervasive existence of IRS indeed an appropriate assumption? Or is abatement rather characterised by fading increasing returns to scale? On the one hand, Andreoni and Levinson (2001, pp. 278 - 281) report empiri-

[5] Fixed costs are conceivable for example in pollution abatement. As a result, poorer countries use dirtier production technologies, as in Stokey (1998), or there is a zero-abatement phase at the beginning, as in Selden and Song (1995). Another example for fixed costs is given by appointment costs of institutions which stick up for the environment, e.g. an environmental protection agency (Jones and Manuelli, 2001). Hence, richer countries are more likely to have powerful environmental institutions.

[6] A technical proof is given by Plassman and Khanna (2004, pp. 6 - 15). The pollution function (5.1) with IRS in abatement is compatible with this notation if $\nu = 1/d$ and $d > 1$.

cal evidence of IRS in abatement. For example, at the plant level, the costs of controlling emissions of large coal-fired boilers decline substantially with the boiler size. At the level of US states, the authors show that "*average pollution abatement costs per dollar of GSP [gross state product] decline with industry size, across states and industries, and over time.*" Moreover, Maradan and Vassiliev (2005) report that the marginal opportunity costs of carbon dioxide abatement, measured as forgone production of output, are negatively associated with income. All these empirical findings can be interpreted as evidence for the existence of IRS in abatement.

On the other hand, there are also legitimate arguments for fading IRS in abatement. First, it is not clear from the outset that doubling both pollution and environmental effort results throughout in more than doubled abated pollution. In contrast, it seems plausible that abating pollution becomes relatively more resource intensive as the last speck of pollution is or must be tackled. Second, abatement activities may be characterised by learning by doing, so that experience in pollution abatement will indeed increase the effectiveness of environmental effort. However, learning curves typically show that the potential gains due to experience decrease with the cumulative activity. Moreover, the potential cost reductions associated with learning are usually higher for infant technologies than for mature technologies (Bramoullé and Olson, 2005). There are no broad empirical estimates of learning curves for pollution abatement so far. The early study of Bellas (1998) can be regarded as an exception. He finds a decreasing cost trend of flue gas desulphurisation units over their lifetimes. Despite the fact that this result can be regarded as evidence for the existence of learning-by-doing effects, no conclusions regarding decreasing learning effects can be drawn by means of this study. Yet, McDonald and Schrattenholzer (2001) compile estimated learning rates for various energy technologies from 26 field studies, and conclude that later data imply lower learning rates, especially for gas turbines and gas turbine combined-cycle power plants.

In sum, there is evidence for the existence of increasing returns to scale in abatement. In addition, it seems more plausible that an abatement technology can indeed exhibit IRS at some stages but not throughout. In other words, with rising environmental effort, the increasing returns to scale in abatement level off.

5.5 New Approach: Fading IRS in Abatement

5.5.1 The General Mechanism

On the basis of the arguments above, a further mechanism to avoid negative pollution becomes obvious: continuous restraint of the degree of the increasing returns to scale. In other words, at the beginning the abatement technology exhibits increasing returns to scale. But with rising abatement activities the IRS get weaker and weaker and approach constant returns to scale (CRS) in the limit. This general mechanism is illustrated in Figure 5.1. The gross pollution function is linear in the polluting activity, while the abatement technology exhibits IRS at the beginning but eventually becomes a linear function too. If the restraint of the degree of IRS is adequately specified, an EKC-conform pollution-income relation would still result, but pollution would never become negative. Pollution would rather approach a non-negative constant.

This procedure does not only constitute a accurate solution to the theoretical problem of negative pollution, but also does well regarding the empirical plausibility of the abatement technology. Moreover, its smooth decline of pollution is more plausible than a steep decline and an abrupt change from positive pollution levels to zero pollution, as would result with the incorporation of a non-negativity constraint for pollution. However, it should be noted that this approach is only applicable to EKC models with explicitly modelled increasing returns to scale in the abatement technology.

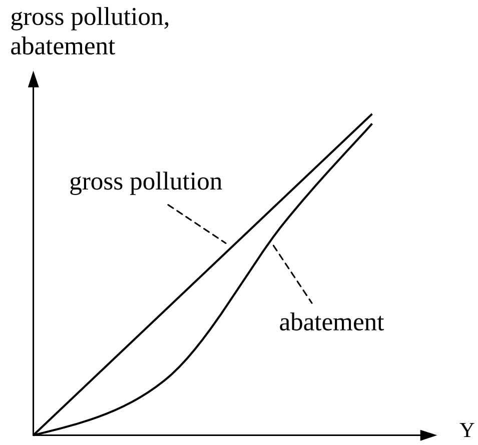


Figure 5.1: Fading IRS in abatement

5.5.2 A Specific Example

To further illustrated this approach, the fading-IRS mechanism is now applied to a dynamic EKC model with a net pollution function in line with equation (5.1). However, the abatement technology is slightly modified. Basically, $B(C, E)$ exhibits IRS but the degree of the IRS steadily declines with increasing environmental effort E. In the limit, $B(C, E)$ is approximately characterised by CRS. The following net pollution function fulfills this property:

$$P = C - C^{\alpha} E^{1-\alpha+\frac{1}{1+E^2}} \tag{5.7}$$

The decreasing degree of IRS is due to the second term in the exponent of E, i.e. $\frac{1}{1+E^2}$, which approaches zero as E becomes large. Of the various arguments for fading IRS in abatement (outlined in Section 5.4 above), the declining learning effects fit best with this particular specification, since it is E and not e.g. P which causes the continuous restraint of the degree of IRS in equation (5.7).

Assuming for illustration purposes that $\alpha = 0.5$, consumption and environmental effort will be approximately equal in the long run. As a result, net pollution approaches zero. It should be noted that the condition $\alpha = 0.5$ for net pollution to be zero with CRS is not a singularity of this specification, but is also valid for the seminal Andreoni and Levinson (2001) model. With CRS and $\alpha > 0.5$, net pollution is monotonically increasing, whereas with CRS and $\alpha < 0.5$, net pollution is monotonically decreasing and, thus, would eventually become negative.

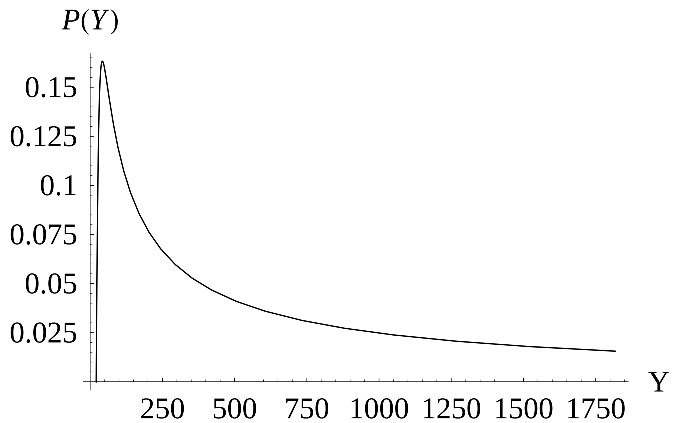


Figure 5.2: Pollution-income relation with fading IRS in abatement

A numerical example with the above net pollution function is provided in Figure 5.2. The illustration is based on an optimisation of the utility function $\int_0^\infty [\log(C - zP)]e^{-\rho t}\,dt$ subject to a standard capital accumulation equation $\dot{K} = AK - \delta K - C - E$, where z reflects the desire for a clean environment, ρ denotes time preference, P is net pollution according to equation (5.7), K is capital, A a constant technology parameter and δ the capital depreciation rate.[7]

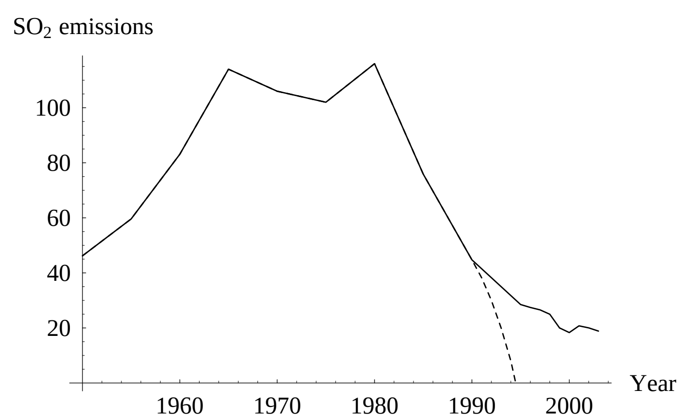
For the relevant range of income the pollution-income relation plotted in Figure 5.2 has all "desired" characteristics: hump-shaped, asymmetric with an upper tail that declines relatively gradually and – most importantly – non-negative net pollution in the long run.[8] Thus, with an appropriate

[7]The following set of parameters is employed: $A = 0.12$, $\delta = 0.06$, $\rho = 0.04$, $\alpha = 0.5$ and $z = 1$. The case $z = 1$ represents an interesting limiting case which is relevant in the sense that the qualitative results largely hold true also for $z < 1$. For a detailed parameter calibration and the consequences of $z < 1$ see Chapter 4, pp. 108 - 112.

[8]According to empirical evidence reported by Grossman and Krueger (1995) the

specification of the net pollution function, the approach with fading IRS in abatement constitutes a promising way of modelling pollution in EKC models with explicit abatement technologies. Unlike e.g. the purely technical solution with a non-negativity constraint (Section 5.2), the approach outlined in this section is able to reflect the real economic relations and the facts observed by the natural sciences.

For example, consider the actual SO_2 emissions for Switzerland for the years 1950 - 2003 reported in Figure 5.3. Since 1980, the SO_2 emissions have been steadily decreasing. However, the rate of decline is not constant. After 1990 the reductions slowed down. Such an emission path is compatible with the argument of fading increasing returns to scale, but not with constant IRS in abatement. With constant IRS in abatement, the emission path would rather continue like the dashed line in Figure 5.3.



Note: SO_2 emissions in Gg.

Source: 1950 - 1989: Swiss Agency for the Environment, Forests and Landscape (1995); 1990 - 2003: Swiss Agency for the Environment, Forests and Landscape (2005).

Figure 5.3: SO_2 emissions for Switzerland, 1950 - 2003.

pollution-income relation should be skewed to the right.

5.6 Summary and Conclusions

Theoretical EKC models with an explicit abatement technology and net pollution as the difference between gross pollution and abatement, often involve that both pollution as a stock variable and pollution as a flow variable can potentially become negative.

In the theoretical literature on the EKC the aspect of negative pollution is usually not adequately addressed. The paper at hand has tried to close this gap. In a first step, two different solution approaches adopted in existing EKC models were discussed. First, the restriction to interior solutions and the consideration of an additional non-negativity constraint for pollution were investigated. It was argued that this procedure is not fully satisfying since it is of a solely technical nature and not due to a more realistic abatement function. Second, an approach employed by Brock and Taylor (2004) was discussed. By converting the original pollution function with net pollution as difference between gross pollution and abatement into a pollution function in line with emission intensities, these authors proposed a smart solution to the problem of negative pollution. However, this approach does not constitute a general solution but its success depends rather on the choice of the "right" functional form for the abatement technology, and in some circumstances additional technological progress is necessary for an hump-shaped pollution-income relation. In a second step, a new approach to avoid negative pollution was introduced. Motivated by the debatable assumption of perpetual increasing returns to scale in abatement, the mechanism of fading IRS was proposed. By a continuous restraint of the IRS until the abatement technology exhibits CRS in the limit, the pollution-income relation can potentially be characterised by non-negative pollution levels in the long run. Even though this new approach is promising, it is not a panacea for the problem of negative pollution. The general applicability is not given since this mechanism can only be employed in EKC models with explicitly modelled IRS in abatement. Furthermore, more research on an appropriate functional specification generating the needed restraint of the degree of IRS is required.

Chapter 6

The Environmental Kuznets Curve – Evidence from Time Series Data for Germany

In recent years, extensive literature on the Environmental Kuznets Curve leading to optimistic policy conclusions has attracted great attention. However, the underlying cross-section estimations are not very reliable. Accordingly, this contribution uses time series data for a single country with reliable data quality: Germany. The results of the traditional reduced-form specification do not support the EKC hypothesis. However, with a specification in the tradition of error correction models, which are more appropriate in the presence of non-stationary time series, it is found that the typical EKC pattern can be confirmed.

6.1 Introduction

Recently, a series of empirical studies about the so-called Environmental Kuznets Curve (hereafter EKC) has been published.[1] The EKC hypothesis postulates that environmental pollution follows an inverted U-shaped curve relative to income. Put differently, environmental quality first decreases with rising income but, after a certain income level has been reached, it begins to recover again. However, the reported empirical results and conclusions are ambiguous. Some authors find evidence for an EKC for different air and water pollutants and other measurements of environmental degradation (e.g. Grossman and Krueger, 1995; Selden and Song, 1994; Cole et al., 1997). Others, on the other hand, report either monotonically increasing or decreasing relationships between pollution and per capita income, or even find no such relationship (e.g. Torras and Boyce, 1998 and partly Shafik, 1994). Nevertheless, the validity of the EKC hypothesis is crucial for possible policy implications. If the hypothesis does not apply, one could argue that "to save the environment and even economic activity from itself, economic growth must cease and the world must make a transition to a steady state economy"(Panayotou 2000, page 1). If, however, the hypothesis applies, the conclusion might be quite different: "But the strong correlation between incomes and the extent to which environmental protection measures are adopted demonstrates that, in the long run, the surest way to improve your environment is to become rich" (Beckerman, 1992, page 491).

Most empirical studies on the EKC hypothesis use cross-country or panel data for their empirical estimations. But the fiercely criticised use of cross-country data suggests that only single-country studies could shed light on the validity of the EKC hypothesis (e.g. Roberts and Grimes, 1997). The following arguments support this view. An EKC found by cross-country estimations could simply reflect the juxtaposition of a positive relationship between

[1] The EKC is named after Simon Kuznets (1955), who found a hump-shaped relationship between income and the inequality of income.

pollution and income in developing countries with a negative one in developed countries, and not a single relationship that applies to both categories of countries. Such an EKC would be a statistical artefact (Vincent, 1997). This argument partly applies also to panel data estimations. Owing to the short length of available time series on pollution, the panel data sets typically contain little or no overlap between observations from developing and developed countries. Low-income observations come from developing countries; high-income observations, on the other hand, from developed countries (Vincent 1997). On account of this fact, the somewhat uncommon conclusion is drawn that for EKC studies time series estimations are to be preferred even to panel data estimations.[2] In principle, the disregard for this juxtaposition is a special case of parameter heterogeneity, which is a frequent problem in the cross-section growth context. It is questionable whether the homogeneity assumption that all estimated coefficients are country-invariant is appropriate for a broad spectrum of countries, reaching from poor developing countries to rich and highly industrialised nations. Possibilities for avoiding the parameter heterogeneity problem are the use of specifications, which allow for varying coefficients, or – as in this paper – data limitation to one single country.[3]

More arguments for the use of time series data are provided by List and Gallet (1999). These authors find very different income turning points across the US states for sulphur dioxide and nitrogen oxide. In other words, the US states do not follow a uniform pollution path. Since US states are commonly and correctly assumed to be more homogenous than most samples of countries, this study backs up the advantage of time series estimations over cross-country studies. If the results of cross-section estimations are generalised, incorrect inferences about the further development of pollutant emissions or

[2]This animadversion does, of course, not apply to panel data studies with a broad and overlapping data set. In this case, panel data estimations are indeed to be preferred to time series estimations with only one country.

[3]For a brief treatise on parameter heterogeneity in the growth context, see Temple (1999).

concentrations could be drawn and, therefore, misleading policies proposed. Similar conclusions are reported by Dijkgraaf and Vollebergh (2005) when comparing time series with panel estimations for carbon dioxide. Estimating the income-emission relation for OECD countries, they find that pooling countries in one panel can bias the estimates and, therefore, the results may not be reliable. Again, the cause of this distortion is the juxtaposition of different income-emission relationships within the pooled countries.

So far, there are only a few studies with time series data for a single country and, as in the case of cross-country studies, the results are mixed. Carson et al. (1997), using US state data between 1988 and 1994, find a negative relationship between seven types of air pollutant emissions and income. Since, for the period under consideration, the per capita income levels of the United States are clearly above the EKC turning points usually calculated by cross-country studies, these results are consistent with the EKC hypothesis. No support for the EKC supposition, however, is given by Vincent (1997). This author reports that the emission profiles that are actually observed in Malaysia do not coincide with those that are predicted by cross-country studies for a country with a per capita GDP like Malaysia. Mostly, the concentration path of pollutants is incorrectly predicted and the changes in pollutant emissions are vastly overstated by cross-country estimations. Applying a somewhat more sophisticated model specification, de Bruyn et al. (1998) find that economic growth has a negative effect on environmental quality, but, despite the increase in emissions due to economic growth, emissions are likely to decline over time, given sufficient technological progress or structural change. On this account, the authors reason that "the presumption that economic growth results in improvements in environmental quality is unsupported by evidence [...]". Unruh and Moomaw (1998) and Moomaw and Unruh (1997) find evidence that the carbon dioxide emission trajectories of sixteen OECD countries follow an inverted U-shaped curve; however, not with respect to income, but with respect to time. The change from an increasing to a decreasing relationship occurred in all countries around 1973 –

the time of the first world-wide oil price shock. Unruh and Moomaw (1998, page 227) conclude that "emissions trajectories would be expected to follow a regular, incremental path until subjected to a shock that leads to the establishment of a new trajectory or attractor."[4] Perman and Stern (2003) use cointegration analysis to test the EKC hypothesis for sulphur emissions. These authors show that the general applicability of of the EKC hypothesis is not granted. The estimation results highly depend on the supposed model specification and on the data set. A historical perspective about the carbon dioxide emissions in Sweden from 1870 – 1997 (Lindmark, 2002) shows that emission fluctuations can be explained mostly by technological and structural change, by economic growth and by changing prices. Recent and more comprehensive surveys of the empirical EKC literature are provided by Copeland and Taylor (2004), Dasgupta et al. (2002) and Stern (2004), among others.[5]

This paper, using time series data for Germany, aims at investigating the relationship between several pollutants and income within a single, developed country. In particular, the following questions are scrutinised. Are the doubts on the suitability of cross-country studies legitimate, i.e. are the results of time series estimations in line with those of cross-country studies? Is the widely used traditional reduced-form equation appropriate for time series estimations? To answer these questions, first the traditional form model with only one independent variable, namely gross domestic product (GDP), is estimated. The estimation results of this simple specification, which was first introduced by Grossman and Krueger (1993), give rise to the supposition that the development of environmental pressure is more complex and that the different stages of environmental degradation cannot be explained by per

[4]However, since the included countries were selected on the basis that their pollution-income relations show evidence of a structural break around 1973, the estimation results are not very representative and, therefore, the conclusion should not be generalised.

[5]Compared to empirical EKC studies, theoretical EKC models are quite rare. Recent contributions are Brock and Taylor (2004), Kelly (2003), Chimeli and Braden (2002), Lieb (2002), Andreoni and Levinson (2001), Bulte and van Soest (2001) or the models presented in Chapters 3 and 4.

capita income alone. Therefore, other variables must have at least as much influence on the environment as income. Different possibilities, such as the incorporation of trade variables or gross value added by the industry sector, which are commonly proposed by theory, are evaluated.

Second, this paper contributes to the EKC literature by applying a model specification that can be regarded as a modified error correction model. The advantages of this specification are the distinction between two different influence channels and the more favourable estimation characteristics in the presence of serial correlation and non-stationarity. Although these results yield better results with regard to the estimation statistics and some evidence for a hump-shaped emission pattern is found, the empirical validity of the EKC hypothesis is not conclusively confirmed.

The remainder of this paper is organised as follows. In Section 6.2, the theoretical framework is set forth. Some explanatory notes to the data are provided in Section 6.3. In Section 6.4, the empirical results are presented and discussed. Finally, Section 6.5 concludes.

6.2 Framework

The non-linear relationship between the indicators of environmental pollution and per capita income is usually specified in a reduced form such as:

$$P_t = \sigma_0 + \sigma_1 Y_t + \sigma_2 Y_t^2 + \sigma_3 Y_t^3 + \sigma_4 V_t + \varepsilon_t \tag{6.1}$$

where P stands for the pollution indicator, Y for income and V for other variables that are supposed to influence pollution; t denotes a time index and ε is the normally distributed error term. An EKC results from $\sigma_1 > 0$, $\sigma_2 < 0$, and $\sigma_3 = 0$. The income level at which environmental degradation begins to decline is called income turning point (ITP). The ITP of an EKC is obtained by setting the first derivation (with respect to income) of equation (6.1) equal to zero and solved for income; this yields $-\sigma_1/2\sigma_2$.[6] With $\sigma_1 > 0$, $\sigma_2 < 0$ and $\sigma_3 > 0$ an N-shaped pattern is obtained, i.e. there is a second turning point, after which the environmental degradation rises again with increasing income. However, investigating the relationship between carbon dioxide and GDP for a subset of OECD countries, Moomaw and Unruh (1997) conclude that an N-shaped curve is more the result of polynomial curve fitting than a reflection of any underlying structural relation. In addition, if an N-shaped pattern is obtained, the second turning point usually occurs at relatively high per capita income levels reached only by very few countries; thus, these results should be viewed with caution. Furthermore, the incorporation of a cubic income term can cause econometric problems due to the multicollinearity of the income variables (linear, quadratic and cubed). Thus, both estimations with and without a cubed income term seem appropriate. An either monotonically increasing or decreasing relationship between income and environmental quality is achieved if only σ_1 is significant (negative or positive sign, respectively), whereas the other coefficients of the income variables, i.e. σ_2 and σ_3, remain insignificant.

While the incorporation of per capita income as an independent variable in single country studies seems undisputed, the choice of the other explanatory variables is not clear, since – contrary to cross-country studies – differences that are country-specific but consistent over time do not matter in time series. For example, it is unnecessary to control for population density, for oil exporting or former communist countries, for literacy rate or political rights. All these variables do not change, or at least not relevantly, over the time period under consideration.

As will be shown in Section 6.4 below, per capita income fails to satisfactorily explain the environmental degradation with regard to economic

[6]Under the assumption $\sigma_3 = 0$. This term should be small relative to mean per capita income, in order for the EKC to turn down at achievable income levels. Moreover, dependent on the scaling of y, $|\sigma_1| > |\sigma_2|$ in order to get a rising curve segment at the beginning.

development. Therefore, the traditional reduced-form equation must be extended. Income can either be included directly in the model as a variable that summarises all effects associated with income, or it can be disaggregated into different channels through which income affects pollution (Grossman, 1995). First, there is a scale effect. Ceteris paribus, more economic activity leads to increased environmental damage, since increasing output requires more natural resources as inputs and causes more emissions and waste as a by-product. Second, structural changes in the economy lead ceteris paribus to altered environmental pressure. During industrialisation (transformation from agricultural to industrial production), environmental degradation tends to increase, whereas during the deindustrialisation phase (from industry to services), the reverse occurs. This argument is based on the legitimate assumption that industrial production is normally more polluting than both the agricultural and the service sectors (Arrow et al., 1995; Suri and Chapman, 1998). This second channel is usually called the composition effect. Third, due to more research and development expenditure, economic growth is usually accompanied by technological progress.[7] Therefore, a replacement of obsolete machineries and technologies with more environmentally friendly ones can be observed. This is labelled the technique effect. Since in this paper pollution data are in the form of aggregate emissions and not concentrations, there is no obvious way to separate scale and technique effects (Cole 2003).[8] Therefore, only the composition effect is specified separately [see equation (6.2) below].

Besides these income-related variables, which do not differ from cross-country studies, other variables influencing pollution come to the fore in

[7]The positive correlation between income and R&D expenditure can be traced back to the uncontested assumption that the demand for environmental quality rises with income.

[8]With concentrations as pollution data, GDP per square kilometre can be used as a proxy for scale and and per capita GDP to appraise technique effects (e.g. Panayotou, 1997). The approximation of environment-related technology levels with a time trend is not satisfactory, albeit this is sometimes done in empirical studies.

studies with time series data. The displacement effect (also referred to as pollution haven hypothesis) relates to the possibility that developed countries may shift pollution-intensive production to developing countries with laxer environmental regulations and import those products. By doing so, developed countries cut back their domestic emissions without having to alter their consumption habits. But overall, there is no world-wide emission reduction or, in other words, only an illusion of sustainability is created (Rees, 1994). The factor endowment hypothesis, however, counteracts the pollution haven hypothesis. It suggests that dirty production, which is usually capital intensive, is located where capital is more abundant, i.e. in developed countries. Antweiler et al. (2001) investigate the consequences of free trade on the environment and find empirical evidence that capital abundance is more important than lax environmental policy. However, Suri and Chapman (1998) incorporate the amount of imported manufactured goods as an additional explanatory variable and find that this leads to significantly higher income turning points than estimations without trade variables. The existence and importance of the displacement effect is also supported by a meta-analysis of twenty-five EKC studies by Cavlovic et al. (2000). If one controls for the countries' trade relations, higher EKC turning points are obtained.

Finally, the reunification of the former East German states with the West German states calls for a dummy variable, if one would also like to use more recent data. From 1992 onwards, the statistical data about pollutant emissions is only published for the reunified Germany and not separately for the two former German republics.

Taking into account the extensions discussed above, the traditional EKC specification [equation (6.1)] becomes:

$$P_t = \sigma_0 + \sigma_1 Y_t + \sigma_2 Y_t^2 + \sigma_3 Y_t^3 + \sigma_4 S_t + \sigma_5 I_t + \sigma_6 D_t + \varepsilon_t \tag{6.2}$$

where Y stands for income and now indicates the net income effect (scale and technique effect), S is the industry share of GDP and represents the composition effect, I is the sum of imports and exports of goods from pollution-intensive production relative to GDP and D is the reunification dummy.

If one uses time series data, two econometric problems – namely the assumption of no serial correlation and of stationarity – must not be neglected.[9] In time series studies, the assumption that errors corresponding to different observations are uncorrelated often fails to prove true. In general, this leads to inefficiency of ordinary least squares. The generalised least squares procedure (GLS) controls for serial correlation and is, therefore, widely applied in time series studies. Besides the favourable characteristics with regard to autocorrelation, the GLS method also produces best linear unbiased estimators if the assumption of homoscedasticity, i.e. equal variances of the error term, is not fulfilled. Therefore, all estimations of equation (6.2) are based on GLS.

Time series are often non-stationary.[10] A regression involving non-stationary time series only leads to sensible results if the series are cointegrated, whereas otherwise such a regression is subject to the spurious regression problem. Cointegration is given if both time series are non-stationary and a linear combination that is itself stationary exists between them. In other words, the non-stationary components of these variables neutralise each other. In our case, none of the considered pollutants is a stationary variable, nor are they cointegrated with GDP in the usual sense.[11] However, since we are not looking at a linear relationship between income and emissions, but rather at an inverted U-shaped or an N-shaped one, income squared and cubed should be added as additional variables while testing for cointegration. If the resulting residuals are stationary, the two time series can be viewed as quasi-cointegrated in the sense that the non-stationary components of the considered time series neutralise each other and, therefore, the estimation results are not spurious. By regressing each pollutant on GDP (with a linear,

[9] Unless otherwise stated, correlation stands for correlation of first order.

[10] Unless otherwise stated, non-stationary and non-stationarity stands for unit root non-stationary and unit root non-stationarity, respectively.

[11] If they were cointegrated in the usual sense, the relation between the two variables would be linear and, therefore, there would be no income turning point. The results of the Dickey Fuller tests for unit root are reported in Table 6.4 in the appendix on page 166.

quadratic and partly a cubed term) and controlling for autocorrelation, the obtained residuals are indeed mostly stationary.[12] In the following, an estimation procedure is considered which deals with serial correlation and the non-stationarity of the time series in an appropriate way.

All estimation specifications considered so far do not distinguish between a long-term income-emission relationship and short-term disturbances from the long-term equilibrium path. A model specification that differentiates between these two effects is the so-called error correction model (ECM), which was popularised by Davidson et al. (1978) in estimating a consumption function for the UK. In the ECM specifications, the relationship between the endogenous variable and the explanatory variable is modelled as follows. The changes in the dependent variable are influenced by changes in the exogenous variable (channel one) and the deviation of the dependent variable from its long-term value in the previous period (channel two). For our purposes, the specification of the ECM equation must be modified, since first the hypothesised long-term relationship is not linear, but follows a hump-shaped or an N-shaped pattern, and second we have more than one exogenous variable (see also Perman and Stern, 2003). Regarding the first channel, we have to include the changes of the squared and cubed income terms as well as of the industry share of GDP and of the trade openness variable. The second channel has to be enlarged analogously. This yields:

$$\begin{aligned}\Delta P_t \;=\;& \psi_0 + \psi_1 \Delta Y_t + \psi_2 \Delta Y_t^2 + \psi_3 \Delta Y_t^3 + \psi_4 \Delta S_t + \psi_5 \Delta I_t \\ & + \psi_6 \left(P_{t-1} - \varphi_0 - \varphi_1 Y_{t-1} - \varphi_2 Y_{t-1}^2 - \varphi_3 Y_{t-1}^3 - \varphi_4 S_{t-1} \right. \\ & \left. - \varphi_5 I_{t-1} - \varphi_6 D_{t-1} \right) + \psi_7 \Delta D_t + \varepsilon_t \end{aligned} \tag{6.3}$$

where Δ denotes a variable's first difference. The whole term in parenthesis, $\left(P_{t-1} - \varphi_0 - \varphi_1 Y_{t-1} - \varphi_2 Y_{t-1}^2 - \varphi_3 Y_{t-1}^3 - \varphi_4 S_{t-1} - \varphi_5 I_{t-1} - \varphi_6 D_{t-1}\right)$, i.e. the deviation from the long-term relation, is called error correction term and coincides with the one-period lagged residuals of the above-mentioned traditional EKC equation [equation (6.2)].

[12] The detailed results are reported in Tables 6.5 and 6.6 in the appendix on page 167.

To potentially obtain a hump-shaped pattern between environmental degradation and income or an EKC, respectively, the coefficient of the error correction term, ψ_6, must be negative. This can be interpreted in the following way. If, in the previous period, the actual emissions were greater than the optimal long-term emissions, the error correction term becomes positive and, together with its negative coefficient, operates towards a smaller or even negative emission growth rate. If, however, the actual emissions were less than the optimal emissions, the error correction term becomes negative and, together with the negative sign of its coefficient, the reverse effect occurs. This does not mean that individuals intend to reduce environmental quality unnecessarily, but that due to socially optimal activities they put up with an increasing emission growth rate. For example, it may be optimal to invest in infrastructure equipment even though this causes higher emissions. In this case, income rises with investments, but emissions temporarily fall below the long-term equilibrium because pollution does not start immediately when the infrastructure is built up. An analogous reasoning applies for an N-shaped pattern. The coefficients of ΔY and ΔY^3, i.e. ψ_1 and ψ_3, are expected to be positive, whereas the coefficient of ΔY^2, i.e. ψ_2, should be negative. As above, a higher industry sector share of GDP should lead to higher emissions. Thus, ψ_4 is expected to be positive. ψ_5 again determines the relative strength of the pollution haven hypothesis relative to the counteracting factor endowment hypothesis.

6.3 Data

6.3.1 Data Source

In this study, per capita emission data are used as indicator for environmental degradation. Ekins (1997) argues that environmental damage is more likely to be related to aggregate emissions than urban concentrations.[13] The following

[13] For a brief treatise on the choice of environmental data, i.e. the advantages and disadvantages of emission and concentration data, see Lieb (2003).

eight pollutants are considered: sulphur dioxide (SO_2), nitrogen oxide (NO_x, as usually measured by nitrogen dioxide NO_2), carbon dioxide (CO_2), carbon monoxide (CO), ammonia (NH_3), methane (CH_4), particulate matter (PM) and non-methane volatile organic compounds (NMVOC). All pollutants are measured in kilograms. Per capita GDP is measured in Euros at 1991 prices, while the imports and exports of goods from pollution-intensive production are set in relation to GDP.[14] Gross value added by sector is gauged by percent of total value added. The time period covers the years 1966 – 1999. All data, i.e. emissions data, GDP, population data, gross value added by sectors, as well as import and export data, are taken from the Statistical Yearbooks for the Federal Republic of Germany (1966 – 2002). Because of availability limitations, all data from 1966 to 1991 represent only the former West Germany, whereas the data from 1992 onwards incorporate all sixteen German Länder.[15] Since empirical work with time series data requires observations over a longer period, one has to accept this data break. To restrict the sample to West Germany and/or up to 1991 is no real alternative, and observations for the years before 1966 are not available.

6.3.2 Descriptive Statistics

If one looks at the time profile of the emissions, several points stand out (see Figure 6.1). Without exception, all pollutant emissions declined in the last few years; however, the rate of the decrease is not equal among the pollutants or over time. In addition, there is no common turnaround for the eight pollutants. In particular, there is no turnaround in the year of reunification. On this account, a potential EKC would not be the result of the incorporation of former East Germany from 1992 on. In the case of CO_2

[14]The following product categories are taken into account: raw materials (apart from foodstuffs), mineral fuels, lubricants, chemicals, manufactured goods, machine and vehicle construction, and various finished products.

[15]Notice that, due to data availability, the value of the dummy variable does not change in the year of German reunification, but only in 1992.

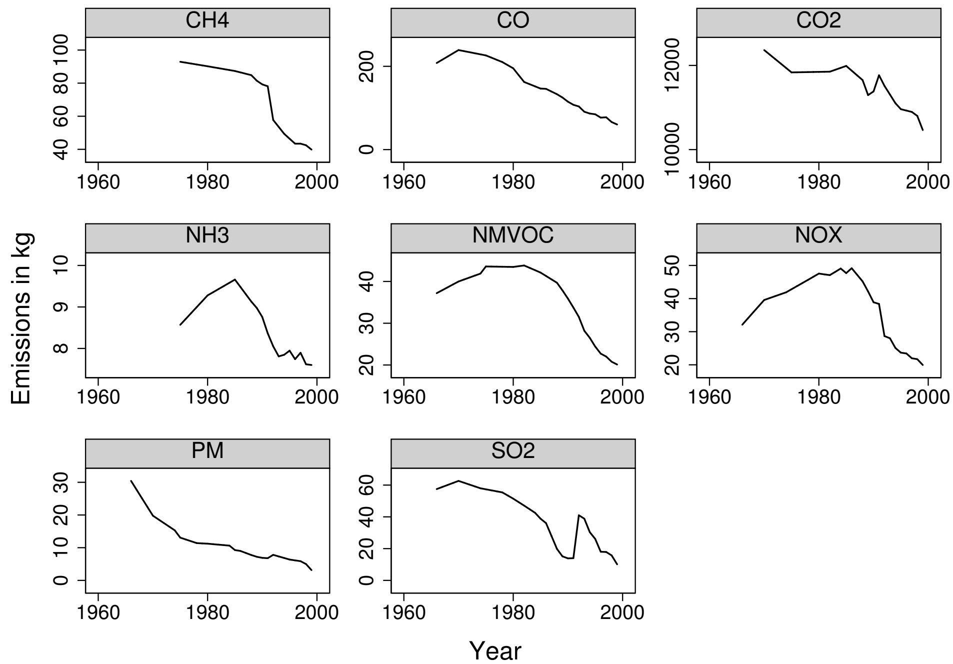


Figure 6.1: Time profiles of the pollutants

and SO_2, one observes a great leap in the first year of reunification. These emission paths can possibly be explained by the fact that the heavily polluting power stations of former East Germany stayed in operation for some years, whereas the replacement of vehicles, which were largely responsible for carbon monoxide and nitrogen oxide emissions, was carried out more quickly.

6.4 Empirical Results and Discussion

In a first step, different estimations of equation (6.2) were carried out for all eight pollutants, i.e. with and without the cubed income term and the additional explanatory variables, respectively. Because of serial correlation, generalised least squares (Cochrane-Orcutt procedure) is required as the estimation technique. Nevertheless, in most estimations the problem of serial correlation cannot be solved by GLS, meaning that the equations are misspecified and an interpretation of the estimated coefficients is not possible.

Problems arise for SO_2, CO_2, PM, CH_4, NMVOC and mostly for CO. In addition, including a cubed income term causes a sign reversal for the income variables in some cases. These coefficients, however, are not significant with the exception of particulate matter. The reason for the sign reversal can be traced back to the very high correlation between the three income variables. Thus, in the following, only the successful examples of these estimations, i.e. the estimations for NO_x and NH_3, are reported and discussed. The results are shown in Tables 6.1 and 6.2, respectively.[16]

For the traditional reduced-form model with only GDP as explanatory variable and without a cubed income term [column (1)], positive linear and negative quadratic income coefficients are obtained. This results in a hump-shaped emissions profile, but only in the case of NO_x are the coefficients significant. The calculated turning point of the NO_x-EKC occurs at a per capita income of € 15,164 (in 1991 prices). This level of per capita income was reached around 1977 and corresponds to roughly USD 14,750 (in 1985 prices).[17] Allowing for a cubed income term [column (5)] results, on the one hand, in the loss of significance for NO_x but, on the other hand, the coefficients of NH_3 are now significant. With the positive coefficient of the cubed income term, the emission profile of ammonia is N-shaped. Therefore, two ITPs are obtained: the first occurs around € 17,500 (USD 17,000), which is somewhat higher than in the case of NO_x; the second emerges around € 23,700, i.e. it lies slightly outside the sample range.[18] The estimated pollution-income relations for NO_x and NH_3 are depicted in Figure 6.2. On the basis of these estimation results, the question on the appropriateness of a cubed income term cannot be conclusively answered. In the case of NH_3, the incorporation

[16] The estimation results of the other six pollutants are reported in Tables 6.7 – 6.12 in the appendix on pages 168 to 173.

[17] The amounts are first converted into USD using the annual mean exchange rate of 1991 (source: http://www.oanda.com) and then deflated using the implicit price deflator for GDP (source: Bureau of Economic Analysis, U.S. Department of Commerce).

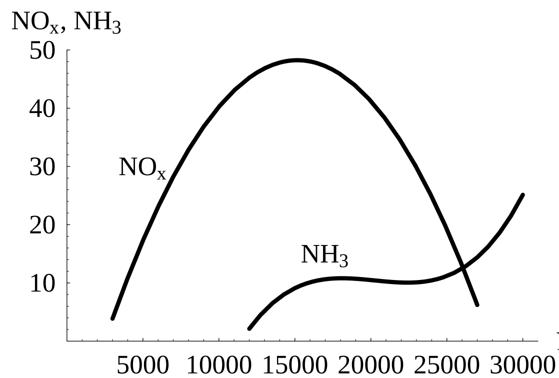
[18] The income turning point of NH_3 is not calculated in column (1), since the income coefficients are not significant.

Table 6.1: Endogenous variable: per capita emissions of NO_x

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	-20.74	-24.54	11.05	-13.91	80.09	69.84	43.76	69.59
	(0.76)	(0.88)	(0.39)	(0.47)	(1.07)	(1.56)	(1.02)	(1.49)
	(0.46)	(0.39)	(0.70)	(0.64)	(0.29)	(0.13)	(0.32)	(0.15)
Y	9.1e-3***	9.9e-3***	8.5e-3***	9.1e-3**	-1.1e-2	-9.2e-3	-8.0e-3	-9.2e-3
	(3.20)	(2.90)	(3.00)	(2.55)	(0.82)	(1.15)	(1.01)	(1.12)
	(0.00)	(0.01)	(0.01)	(0.02)	(0.42)	(0.26)	(0.32)	(0.27)
Y^2	-3.0e-7***	-3.2e-7***	-2.8e-7***	-3.0e-7***	9.3e-7	1.0e-6**	9.4e-7*	1.0e-6**
	(4.00)	(3.41)	(3.71)	(3.03)	(1.22)	(2.13)	(1.96)	(2.06)
	(0.00)	(0.00)	(0.00)	(0.01)	(0.23)	(0.04)	(0.06)	(0.05)
Y^3					-2.4e-11	-3.0e-11***	-2.8e-11***	-3.0e-11***
					(1.67)	(3.15)	(2.93)	(3.03)
					(0.11)	(0.00)	(0.01)	(0.01)
S		-0.08		-0.07		-0.36**		-0.36*
		(0.34)		(0.27)		(2.24)		(1.74)
		(0.73)		(0.79)		(0.03)		(0.09)
I			-11.57	-11.50			11.89	0.23
			(1.21)	(1.18)			(1.52)	(0.02)
			(0.24)	(0.25)			(0.14)	(0.98)
D	-10.03***	-10.20***	-11.11***	-11.23***	-10.07***	-11.02***	-8.79***	-10.99***
	(9.31)	(8.53)	(7.98)	(7.34)	(9.41)	(9.86)	(6.16)	(6.15)
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
adj. R^2	0.84	0.84	0.82	0.82	0.87	0.97	0.97	0.97
DW	1.93	1.90	1.83	1.82	1.99	1.69	1.74	1.69
N. of obs.	33	33	33	33	33	33	33	33
ρ	0.88	0.87	0.90	0.90	0.82	0.38	0.32	0.38
ITP 1[a]	15,164	15,321	15,182	15,371				

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level
[a] in € at '91 prices

results in a change from an inverted U-shaped to an N-shaped pattern, while in the case of NO_x a sign reversal and a loss of significance are observed, presumably due to multicollinearity.[19]



Note: NO_X and NH_3 emissions in kg; Y (GDP) in 1991 Euros.

Figure 6.2: Estimated pollution-income relation for NO_X and NH_3

In comparison with cross-country studies, the turning point of nitrogen oxide matches that of other estimations; in Selden and Song (1994), the curve turns down at about USD 11,000, in Cole et al. (1997) between 14,700 and USD 17,600 and, finally, Grossman (1995) reports a turning point of USD 18,453. Although Carson et al. (1997) report a monotonically decreasing relationship between NO_x emissions and GDP for the US, this result is not inconsistent with the EKC pattern found here, since they use only data from 1988 to 1994. In this period, the NO_x emissions in Germany decreased as well. This follows directly from the calculated income turning point, which was reached not later than 1977. Comparisons of the ITPs for ammonia with other estimations are not possible, since to my knowledge ammonia is not considered in any other EKC study.

When incorporating gross value added of the industry sector [(columns (2) and (6)] the estimation results of NO_x do not change notably; the industry share shows no significant influence. However, the income coefficients are

[19]A sign reversal and partly a loss of significance is also found for CO_2, PM, CH_4 and NMVOC.

Table 6.2: Endogenous variable: per capita emissions of NH_3

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	6.31	-8.61***	-8.66***	-8.52***	-138.8***	-130.6***	-72.8***	-94.0***
	(0.81)	(2.95)	(3.40)	(3.72)	(5.01)	(3.52)	(3.87)	(3.99)
	(0.43)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Y	5.8e-4	2.6e-3***	2.0e-3***	2.1e-3***	2.3e-2***	2.1e-2***	1.2e-2***	1.5e-2***
	(0.75)	(8.62)	(7.25)	(8.11)	(5.16)	(3.71)	(4.10)	(4.22)
	(0.46)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Y^2	-2.3e-8	-7.7e-8***	-6.2e-8***	-6.7e-8***	-1.1e-6***	-1.1e-6***	-6.1e-7***	-7.8e-7***
	(1.18)	(9.17)	(8.35)	(9.17)	(4.92)	(3.51)	(3.83)	(3.98)
	(0.25)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Y^3					1.9e-11***	1.8e-11***	9.5e-12***	1.3e-11***
					(4.64)	(3.26)	(3.44)	(3.66)
					(0.00)	(0.00)	(0.00)	(0.00)
S		-0.10**		-0.03		-9.7e-3		0.04
		(4.55)		(1.09)		(0.32)		(1.37)
		(0.00)		(0.29)		(0.75)		(0.19)
I			4.56***	3.81***			3.14***	3.68***
			(6.00)	(3.60)			(4.24)	(4.36)
			(0.00)	(0.00)			(0.00)	(0.00)
D	-0.35**	-0.67***	0.14	0.01	-0.37***	-0.40***	-0.04	0.11
	(2.74)	(4.75)	(1.00)	(0.06)	(3.24)	(2.86)	(0.32)	(0.68)
	(0.01)	(0.00)	(0.33)	(0.96)	(0.00)	(0.01)	(0.75)	(0.51)
adj. R^2	0.73	0.97	0.97	0.98	0.95	0.95	0.98	0.98
DW	2.29	2.03	1.70	1.84	2.09	2.18	2.24	2.07
N. of obs.	24	24	24	24	24	24	24	24
ρ	0.80	-0.00	0.13	0.00	0.33	0.32	0.18	0.20
ITP 1[a]		16,947	16,319	16,357	18,093	17,575	16,969	17,124
ITP 2[a]					22,409	23,187	25,353	23,882

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level
[a] in € at '91 prices

stable in size and the ITP is only slightly higher than before. In the case of ammonia, now both the estimation with and without cubed income are significant, with a slightly lower ITP in the latter case. Still, the GDP share of the industry sector does not have the predicted positive sign. This result is difficult to explain, since the assumption that the industry sector is more polluting than the agriculture and service sectors is plausible and not at all controversial in literature.

The estimation results of columns (3) and (7) reveal ambiguous information about the relative strength of the displacement effect and the factor endowment hypothesis. For NO_x no significant result is obtained. This could be interpreted in the sense that the two effects offset each other. For ammonia, however, a positive sign results. This means that with increasing trade openness emissions also rise. Therefore, the factor abundance hypothesis is supported. The calculated income turning points match those of the previous specifications. The estimations with both the GDP share of the industry sector as well as the trade openness do not give many new insights [columns (4) and (8)]. The main reason may be that the two variables are highly correlated (about 0.9). Apart from that, the same remarks as for the previous estimations apply here.

These estimations clearly show that the existence of an EKC for a single country cannot be supported on the basis of the traditional reduced-form specification. This result contradicts the majority of cross-country or panel data EKC studies. However, as outlined in Section 6.2 above, the reduced-form specification is not appropriate for a time series analysis without restrictions. More sophisticated specifications are to be preferred.

The results of equation (6.3), which follows the error correction model tradition, are set forth in Table 6.3. For each pollutant only its best fitted estimation is shown, since the different specifications yield similar results.[20] Concerning the incorporation of additional explanatory variables, Table 6.3

[20]The complete estimation results, i.e. all eight different estimations for each pollutant, are reported in Tables 6.13 – 6.20 in the appendix on pages 174 to 181.

Table 6.3: Endogenous variable: first difference of pollutant emissions

	SO_2	NO_x	CO_2	PM	CO	NH_3	CH_4	NMVOC
const	-2.87**	-0.48	-101.6	-0.10	-5.30***	0.09**	-1.76**	-0.71
	(2.28)	(1.23)	(1.46)	(0.42)	(2.89)	(2.78)	(2.81)	(1.13)
	(0.03)	(0.23)	(0.16)	(0.68)	(0.01)	(0.01)	(0.01)	(0.27)
ΔY	8.0e-3	5.9e-3*	2.8e-1	3.7e-3*	2.1e-3	1.8e-2***	7.3e-4	2.0e-3
	(1.19)	(1.88)	(0.57)	(1.98)	(0.04)	(6.93)	(0.11)	(0.30)
	(0.24)	(0.07)	(0.57)	(0.06)	(0.97)	(0.00)	(0.91)	(0.77)
ΔY^2	-2.4e-7	-1.8e-7*	-4.6e-6	-1.1e-7*	-1.3e-7	-9.5e-7***	-1.4e-8	-1.4e-7
	(1.21)	(1.97)	(0.32)	(1.89)	(0.04)	(6.55)	(0.08)	(0.34)
	(0.24)	(0.06)	(0.75)	(0.07)	(0.97)	(0.00)	(0.94)	(0.74)
ΔY^3					1.7e-12	1.6e-11***		2.4e-12
					(0.02)	(6.10)		(0.29)
					(0.98)	(0.00)		(0.78)
ΔS	-0.19		-11.48		2.12**	0.12***	0.17	
	(0.33)		(0.36)		(2.09)	(4.08)	(0.73)	
	(0.74)		(0.73)		(0.05)	(0.00)	(0.48)	
ΔI					-9.43	2.66***		
					(0.29)	(4.22)		
					(0.77)	(0.00)		
ECT^{b}	-0.36**	-0.18**	-0.63**	-0.18***	-0.36***	-0.58***	-0.59***	-0.52***
	(2.36)	(2.16)	(2.55)	(4.80)	(3.45)	(4.08)	(4.11)	(4.41)
	(0.03)	(0.04)	(0.02)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
ΔD	28.86***	-9.28***	-113.5	1.30**	4.41	0.01	-17.12***	0.26
	(13.39)	(8.45)	(0.89)	(2.63)	(0.97)	(0.07)	(22.51)	(0.67)
	(0.00)	(0.00)	(0.38)	(0.01)	(0.34)	(0.95)	(0.00)	(0.51)
adj. R^2	0.87	0.77	0.33	0.57	0.49	0.92	0.97	0.42
DW	1.95	2.03	1.46	1.64	2.04	2.08	1.88	1.92
N. of obs.	32	32	28	32	32	23	23	32
ρ	0.56	0.19	0.48	0.23	0.29	-0.40	0.68	0.87

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level
[b] ECT: particular error correction term, i.e. with or without Y^3, S and I.

shows that a cubed income term as well as a trade openness variable do not greatly improve the estimation's explanatory power. The industry sector share of GDP, on the other hand, improves the results in most cases.

Analysing the estimation results in detail, several things strike the observer's eye. First, the coefficients of the first differences of the income variables are mostly not significant. Only in the cases of NO_x, PM and NH_3 significant influences can be observed. However, the signs of the income variables are as expected. As before, the incorporation of a cubed income term sometimes leads to a sign reversal in the income variables. Again, this must be attributed to the multicollinearity of the income variables. Second, and contrary to the estimations of the traditional reduced-form model, here the significant coefficients for the industry sector share of GDP have the expected positive sign (with the exception of NO_x). This means that the more important the industry sector is, the higher are the emissions. Third, the absence and/or the non-significance of the trade openness variable confirms the results of the reduced-form estimations. Either foreign trade does not have an influence on emissions, or the factor abundance hypothesis and the pollution haven hypothesis offset each other.[21] Fourth and most importantly, the coefficients of the error correction term, i.e. ECT, are all significant and – as expected – negative. Thus, these results can be interpreted in the sense that changes in income only have an influence through the second channel. Deviations from the long-term relationship, which is specified to be either hump-shaped or N-shaped, are corrected in the next period. Therefore, even if there is no direct influence through the first channel, the significant results of the second channel suggest an EKC pattern for these pollutants.[22]

[21]Exceptions are ammonia and nitrogen oxide: the positive coefficient of ammonia supports the factor endowment hypothesis, while the negative coefficient of nitrogen oxide (not shown in Table 6.3) endorses the pollution haven hypothesis.

[22]The hump-shaped pattern is traced back to the non-linear specification of the two influence channels in equation (6.3).

However, there is one reason why this interpretation is debatable. If environmental degradation indeed follows a hump-shaped curve, this result should already have been found in equation (6.2). But there, the EKC hypothesis could only be verified for NO_x and NH_3. On the other hand, one can argue that if the distinction between the two different channels, i.e. income changes and deviations from the optimal long-term relation, is important, specifications where this differentiation is not made could lead to distorted results and that, therefore, estimation specification with different channels should be preferred.

6.5 Summary and Conclusions

Using time series data for Germany instead of cross-country or panel data and testing different specifications to gain new insights into the EKC hypothesis for different pollutants, the estimation results remain ambiguous. First, the traditional reduced-form model and some extensions with additional explanatory variables – namely the trade relations and the industry sector share of GDP – are estimated. For nitrogen oxide and mostly for ammonia, an EKC or N-shaped pattern is found, with income turning points around € 15,200 and 17,500, respectively. Thus, for these two pollutants, the results of most cross-country studies can be confirmed. However and more importantly, the other six pollutants do not show clear results. Either the t-statistics are unsatisfactory, or the Durbin-Watson tests give rise to a rejection of these simple model specifications. Astonishingly, this is valid not only with respect to a possible EKC pattern, i.e. a positive linear income term together with a negative quadratic one, but also with respect to monotonically increasing or decreasing development paths of the considered harmful chemical emissions. These results indicate clearly that cross-country studies provide unreliable estimations. Second, and because of the variables' non-stationarity and motivated by error correction models, equations are estimated that distinguish between two different influence channels. But contrary to the well-known error correction models (e.g. for a consumption function), the long-term relationship is specified as a non-linear, i.e. hump-shaped function. The estimations show that the deviations from the long-term optimal value have a significant influence on pollutant emissions. Changes in income or the sectoral and/or foreign trade structure, however, do not have a prominent impact. Nevertheless, the results of the modified error correction model with the underlying non-linear long-term relation give some evidence for the existence of EKCs within a single country.

Summarising all presented estimations, one has to admit that the question of whether EKCs really exist for a single country is not conclusively answered. The estimations of the traditional reduced-form specification do no show a clear and consistent pattern. In addition, the estimation results are not very robust regarding the incorporation of additional explanatory variables. On the other hand, the modified error correction specification is more supportive of the EKC hypothesis. As a result, general policy recommendations with regard to the environment should only cautiously rely on the EKC approach.

In conclusion, two points must be addressed. First, the quality and, for the most part, quantity of the available data is limited. It would be helpful for empirical researchers if they could access a more widespread data pool. Second, it is likely that imported explanatory variables are still omitted in the model specifications. Future research and especially theoretical work on the EKC hypothesis for a single country may lead to more adequate model specifications. Further empirical studies should maybe adhere less to the traditional reduced-form model, but rather enlarge the well-known specifications with additional structural variables or use completely different approaches, e.g. non-linear estimation equations.[23]

[23]Meaning non-linear in parameters.

6.6 Appendix

6.6.1 Tests for Unit Root and Quasi-Cointegration

In Table 6.4 the Dickey-Fuller tests for unit root of GDP and the eight considered pollutants are reported. As one can see, for all time series (with the exception of particulate matter) the null hypothesis of unit root cannot be rejected at the usual significance levels. Therefore, only the time series for particulate matter is a stationary one.

Table 6.4: Dickey-Fuller test for unit root

	N. of obs.	Test Statistics	5% Critical Value*	Approx. p-value**
GDP	33	-0.901	-2.978	0.7876
SO_2	33	-0.272	-2.978	0.9294
NO_x	33	0.671	-2.978	0.9892
CO_2	29	0.496	-2.989	0.9848
PM	33	-6.545	-2.978	0.000
CO	33	1.976	-2.978	0.9986
NH_3	24	0.450	-3.000	0.9833
CH_4	24	0.700	-3.000	0.9898
NMVOC	33	3.182	-2.978	1.000

* The critical values are linearly interpolated from the table of values that appears in Fuller (1976).
** The MacKinnon approximate p-values use the regression surface published in MacKinnon (1994).

In Tables 6.5 and 6.6 the results of the tests for quasi-cointegration (as described in the main text) are reported. More precisely, each pollutant is regressed on GDP, GDP squared, GDP cubed (Table 6.6 only) and the dummy variable for reunification using GLS (Cochrane-Orcutt procedure) as estimation technique. The resulting residuals of these regressions are then tested for unit root. If the null hypothesis of unit root can be rejected, the residuals can be considered as stationary. Analogous to a standard test for cointegration (see e.g. Pindyck/Rubinfeld 1998, page 513ff), stationary residuals are the critical condition for quasi-cointegration between the two considered time series. Here, as one can see, the following pollutants are cointegrated with GDP, at least at the ten percent significance level: (i) with a linear and quadratic GDP term: NO_x, CO_2, PM, CO, and NH_3; (ii) with a linear, quadratic and cubed GDP term: NO_x, CO_2, PM, NH_3 and nearly NMVOC.

Table 6.5: Dickey-Fuller test for unit root (quasi-cointegration test I)

	N. of obs.	Test Statistics	5% Critical Value*	Approx. p-value**
SO_2	33	-2.377	-2.978	0.1484
NO_x	33	-2.650	-2.978	0.0830
CO_2	29	-2.872	-2.989	0.0487
PM	33	-9.949	-2.978	0.0000
CO	33	-2.835	-2.978	0.0535
NH_3	24	-3.651	-3.000	0.0049
CH_4	24	0.712	-3.000	0.9901
NMVOC	33	-2.135	-2.978	0.2306

* The critical values are linearly interpolated from the table of values that appears in Fuller (1976).
** The MacKinnon approximate p-values use the regression surface published in MacKinnon (1994).

Table 6.6: Dickey-Fuller test for unit root (quasi-cointegration test II)

	N. of obs.	Test Statistics	5% Critical Value*	Approx. p-value**
SO_2	33	-2.219	-2.978	0.1993
NO_x	33	-3.262	-2.978	0.0167
CO_2	29	-2.963	-2.989	0.0385
PM	33	-9.640	-2.978	0.0000
CO	33	0.409	-2.978	0.9818
NH_3	24	-10.912	-3.000	0.0000
CH_4	24	0.511	-3.000	0.9852
NMVOC	33	-2.565	-2.978	0.1004

* The critical values are linearly interpolated from the table of values that appears in Fuller (1976).
** The MacKinnon approximate p-values use the regression surface published in MacKinnon (1994).

6.6.2 Additional Econometric Results

In the Tables 6.7 to 6.12 the estimation results of equation (6.2) for the pollutants SO_2, CO_2, PM, CO, CH_4 and NMVOC are reported. As stated in the main text, these estimation results should be interpreted with caution, since the Durbin-Watson statistics do not satisfy the usual significance criterions and the coefficients of the estimated variables are often not significant.

Table 6.7: Endogenous variable: per capita emissions of SO_2

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	-28.61	-59.25	-51.81	-54.10	-138.0	-132.2	-106.7	-103.0
	(0.56)	(1.02)	(1.10)	(0.90)	(0.67)	(0.65)	(0.55)	(0.49)
	(0.58)	(0.31)	(0.28)	(0.38)	(0.51)	(0.52)	(0.59)	(0.63)
Y	1.5e-2***	1.1e-2	1.8e-2***	1.1e-2	3.5e-2	2.4e-2	2.8e-2	2.0e-2
	(2.64)	(1.65)	(3.32)	(1.60)	(0.96)	(0.66)	(0.81)	(0.55)
	(0.01)	(0.11)	(0.00)	(0.12)	(0.35)	(0.51)	(0.42)	(0.59)
Y^2	-6.5e-7***	-4.7e-7***	-6.8e-7***	-4.6e-7**	-1.8e-6	-1.3e-6	-1.3e-6	-1.0e-6
	(3.96)	(2.46)	(4.54)	(2.30)	(0.85)	(0.59)	(0.63)	(0.46)
	(0.00)	(0.02)	(0.00)	(0.03)	(0.40)	(0.56)	(0.54)	(0.65)
Y^3					2.3e-11	1.5e-11	1.2e-11	1.0e-11
					(0.55)	(0.37)	(0.29)	(0.25)
					(0.59)	(0.71)	(0.77)	(0.80)
S		1.24**		1.06*		1.21**		1.05*
		(2.22)		(1.77)		(2.13)		(1.72)
		(0.03)		(0.09)		(0.04)		(0.10)
I			-43.62*	-27.52			-42.50	-26.72
			(1.76)	(1.06)			(1.67)	(1.00)
			(0.09)	(0.30)			(0.11)	(0.33)
D	26.04***	28.35***	21.82***	25.35***	25.88***	28.24***	21.84***	25.39***
	(8.25)	(8.99)	(5.55)	(5.96)	(8.08)	(8.78)	(5.47)	(5.87)
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
adj. R^2	0.84	0.84	0.87	0.83	0.83	0.83	0.86	0.82
DW	1.20	1.29	1.25	1.25	1.19	1.28	1.24	1.25
N. of obs.	33	33	33	33	33	33	33	33
ρ	0.70	0.76	0.67	0.78	0.71	0.76	0.68	0.79

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level

Table 6.8: Endogenous variable: per capita emissions of CO_2

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	6.2e3*	4.4e3	6.0e3	4.4e3	3.4e4*	2.1e4	3.1e4*	2.1e4
	(1.72)	(1.41)	(1.71)	(1.37)	(2.01)	(1.11)	(1.79)	(1.09)
	(0.10)	(0.17)	(0.10)	(0.19)	(0.06)	(0.28)	(0.09)	(0.29)
Y	0.70*	0.60*	0.73*	0.61*	-3.93	-2.11	-3.53	-2.11
	(1.77)	(1.96)	(1.89)	(1.80)	(1.38)	(0.69)	(1.20)	(0.68)
	(0.09)	(0.06)	(0.07)	(0.09)	(0.18)	(0.49)	(0.24)	(0.51)
Y^2	-2.1e-5*	-1.7e-5*	-2.2e-5**	-1.7e-5*	2.3e-4	1.3e-4	2.1e-4	1.3e-4
	(2.01)	(1.98)	(2.10)	(1.86)	(1.47)	(0.80)	(1.31)	(0.78)
	(0.06)	(0.06)	(0.05)	(0.08)	(0.16)	(0.43)	(0.20)	(0.45)
Y^3					-4.6e-9	-2.8e-9	-4.3e-9	-2.8e-9
					(1.59)	(0.90)	(1.44)	(0.88)
					(0.13)	(0.38)	(0.16)	(0.39)
S		49.50*		48.67		41.43		40.46
		(1.91)		(1.64)		(1.48)		(1.25)
		(0.07)		(0.12)		(0.15)		(0.22)
I			-844.96	-73.78			-851.8	-85.86
			(0.69)	(0.06)			(0.71)	(0.06)
			(0.50)	(0.96)			(0.48)	(0.95)
D	-275.60*	-145.56	-354.27*	-155.23	-234.6	-143.6	-324.1	-155.3
	(1.87)	(0.94)	(1.84)	(0.68)	(1.59)	(0.92)	(1.66)	(0.66)
	(0.07)	(0.36)	(0.08)	(0.50)	(0.13)	(0.37)	(0.11)	(0.51)
adj. R^2	0.54	0.70	0.58	0.69	0.72	0.73	0.71	0.72
DW	1.33	1.49	1.34	1.48	1.42	1.49	1.42	1.49
N. of obs.	29	29	29	29	29	29	29	29
ρ	0.68	0.55	0.64	0.55	0.52	0.51	0.52	0.51

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level

Table 6.9: Endogenous variable: per capita emissions of PM

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	-11.72	-4.80	-13.24	-5.92	86.30**	84.36**	87.68**	88.77**
	(0.91)	(0.39)	(1.00)	(0.47)	(2.73)	(2.58)	(2.73)	(2.70)
	(0.37)	(0.70)	(0.33)	(0.64)	(0.01)	(0.02)	(0.01)	(0.01)
Y	2.7e-3*	1.3e-3	2.8e-3*	1.4e-3	-1.7e-2***	-1.6e-2***	-1.7e-2***	-1.8e-2***
	(1.99)	(0.89)	(2.00)	(0.91)	(2.99)	(2.79)	(3.09)	(3.04)
	(0.06)	(0.38)	(0.06)	(0.37)	(0.01)	(0.01)	(0.01)	(0.01)
Y^2	-9.1e-8**	-5.2e-8	-9.4e-8**	-5.5e-8	1.1e-6***	1.1e-6***	1.1e-6***	1.2e-6***
	(2.49)	(1.26)	(2.48)	(1.28)	(3.28)	(3.09)	(3.39)	(3.37)
	(0.02)	(0.22)	(0.02)	(0.21)	(0.00)	(0.01)	(0.00)	(0.00)
Y^3					-2.3e-11***	-2.2e-11***	-2.4e-11***	-2.4e-11***
					(3.52)	(3.35)	(3.63)	(3.62)
					(0.00)	(0.00)	(0.00)	(0.00)
S		0.16		0.16		0.03		-0.02
		(1.47)		(1.39)		(0.25)		(0.13)
		(0.15)		(0.18)		(0.81)		(0.90)
I			1.79	1.47			3.85	3.99
			(0.39)	(0.31)			(0.91)	(0.92)
			(0.70)	(0.76)			(0.37)	(0.37)
D	1.02*	1.30**	1.20*	1.44*	1.18**	1.21**	1.59**	1.59**
	(1.93)	(2.27)	(1.74)	(1.87)	(2.51)	(2.32)	(2.58)	(2.37)
	(0.06)	(0.03)	(0.09)	(0.07)	(0.02)	(0.03)	(0.02)	(0.03)
adj. R^2	0.36	0.50	0.31	0.46	0.39	0.37	0.39	0.37
DW	1.44	1.45	1.42	1.45	1.63	1.63	1.62	1.61
Number of obs.	33	33	33	33	33	33	33	33
ρ	0.86	0.83	0.86	0.84	0.90	0.89	0.91	0.91

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level

Table 6.10: Endogenous variable: per capita emissions of CO

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	237.89	119.85	200.80*	120.79	-6.9e3***	-490.5	-583.5*	-418.5
	(1.69)	(1.21)	(1.89)	(1.26)	(3.82)	(1.56)	(1.71)	(1.36)
	(0.10)	(0.24)	(0.07)	(0.22)	(0.00)	(0.13)	(0.10)	(0.19)
Y	9.5e-3	-1.2e-2	1.4e-2	-8.3e-3	1.4e-1**	9.9e-2*	1.5e-1**	9.0e-2
	(0.61)	(1.07)	(1.17)	(0.73)	(2.28)	(1.77)	(2.51)	(1.64)
	(0.55)	(0.30)	(0.25)	(0.47)	(0.03)	(0.09)	(0.02)	(0.11)
Y^2	-7.5e-7*	7.6e-8	-7.3e-7**	1.7e-8	-7.3e-6*	-6.4e-6*	-8.9e-6**	-5.7e-6*
	(1.74)	(0.23)	(2.19)	(0.05)	(1.96)	(1.97)	(2.45)	(1.80)
	(0.09)	(0.82)	(0.04)	(0.96)	(0.06)	(0.06)	(0.02)	(0.08)
Y^3					1.3e-10	1.2e-10*	1.6e-10**	1.1e-10*
					(1.68)	(1.99)	(2.22)	(1.80)
					(0.10)	(0.06)	(0.04)	(0.08)
S		5.57***		5.00***		5.28***		4.79***
		(6.02)		(5.32)		(6.02)		(5.31)
		(0.00)		(0.00)		(0.00)		(0.00)
I			-162.10***	-78.17*			-170.2***	-68.50*
			(3.09)	(1.92)			(3.45)	(1.73)
			(0.00)	(0.07)			(0.00)	(0.10)
D	-5.53	5.69	-20.72**	-2.88	1.40	4.79	-22.74***	-2.68
	(0.77)	(1.10)	(0.28)	(0.43)	(0.26)	(0.97)	(2.83)	(0.41)
	(0.45)	(0.28)	(0.02)	(0.67)	(0.80)	(0.34)	(0.01)	(0.68)
adj. R^2	0.82	0.91	0.91	0.92	0.26	0.93	0.95	0.93
DW	1.11	1.33	1.64	1.41	1.43	1.41	1.70	1.49
N. of obs.	33	33	33	33	33	33	33	33
ρ	0.77	0.78	0.70	0.79	0.99	0.77	0.59	0.77
ITP 1[a]							13,386	
ITP 2[a]							24,491	

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level
[a] in € at '91 prices

Table 6.11: Endogenous variable: per capita emissions of CH_4

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	-1.5e3***	42.29	-1.6e3***	43.27	-1.2e3**	379.7	-1.3e3**	379.7
	(3.28)	(0.40)	(3.45)	(0.39)	(2.57)	(0.86)	(2.73)	(0.83)
	(0.00)	(0.70)	(0.00)	(0.70)	(0.02)	(0.40)	(0.01)	(0.42)
Y	9.7e-3**	2.6e-3	9.3e-3**	2.5e-3	-1.7e-2	-5.1e-2	-2.0e-2	-5.1e-2
	(2.27)	(0.21)	(2.18)	(0.20)	(0.45)	(0.76)	(0.53)	(0.73)
	(0.03)	(0.83)	(0.04)	(0.85)	(0.66)	(0.46)	(0.60)	(0.47)
Y^2	-2.6e-7**	-1.4e-7	-2.5e-7**	-1.4e-7	1.2e-6	2.7e-6	1.4e-6	2.7e-6
	(2.19)	(0.45)	(2.11)	(0.42)	(0.59)	(0.80)	(0.67)	(0.77)
	(0.04)	(0.66)	(0.05)	(0.68)	(0.56)	(0.44)	(0.51)	(0.45)
Y^3					-2.7e-11	-5.0e-11	-3.0e-11	-5.0e-11
					(0.71)	(0.87)	(0.79)	(0.84)
					(0.48)	(0.39)	(0.44)	(0.41)
S		1.04**		1.04**		1.08**		1.08**
		(2.33)		(2.26)		(2.47)		(2.38)
		(0.03)		(0.04)		(0.02)		(0.03)
I			13.08	-0.40			13.71	-0.15
			(1.07)	(0.03)			(1.11)	(0.01)
			(0.30)	(0.98)			(0.28)	(0.99)
D	-18.89***	-19.14***	-17.48***	-19.18***	-18.89***	-19.23***	-17.42***	-19.25***
	(14.60)	(11.48)	(9.52)	(8.67)	(14.42)	(11.38)	(9.38)	(8.33)
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
adj. R^2	0.91	0.96	0.91	0.95	0.91	0.97	0.91	0.96
DW	1.16	1.50	1.16	1.50	1.21	1.49	1.22	1.49
N. of obs.	24	24	24	24	24	24	24	24
ρ	0.99	0.77	0.99	0.77	0.99	0.71	0.99	0.71

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level

Table 6.12: Endogenous variable: per capita emissions of NMVOC

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	2.76	17.29	0.61	14.26	57.33	60.33	54.44	56.93
	(0.13)	(0.79)	(0.03)	(0.63)	(0.99)	(1.11)	(0.91)	(1.02)
	(0.90)	(0.44)	(0.98)	(0.53)	(0.33)	(0.28)	(0.37)	(0.32)
Y	6.5e-3***	3.1e-3	6.6e-3***	3.3e-3	-3.9e-3	-5.1e-3	-3.5e-3	-4.9e-3
	(2.95)	(1.19)	(2.94)	(1.23)	(0.38)	(0.53)	(0.34)	(0.49)
	(0.01)	(0.25)	(0.01)	(0.23)	(0.71)	(0.60)	(0.74)	(0.63)
Y^2	-2.4e-7***	-1.5e-7**	-2.5e-8***	-1.5e-7**	3.9e-7	3.6e-7	3.7e-7	3.5e-7
	(4.22)	(2.08)	(4.15)	(2.12)	(0.65)	(0.63)	(0.60)	(0.60)
	(0.00)	(0.05)	(0.00)	(0.04)	(0.52)	(0.53)	(0.55)	(0.56)
Y^3					-1.3e-11	-1.0e-11	-1.2e-11	-9.9e-12
					(1.07)	(0.90)	(1.02)	(0.87)
					(0.30)	(0.38)	(0.32)	(0.39)
S		0.41**		0.41**		0.39*		0.39*
		(2.05)		(2.05)		(2.00)		(2.01)
		(0.05)		(0.05)		(0.06)		(0.06)
I			3.50	4.35			3.10	4.23
			(0.46)	(0.60)			(0.41)	(0.58)
			(0.65)	(0.55)			(0.69)	(0.57)
D	-2.60***	-1.88**	-2.28**	-1.46	-2.65***	-1.91**	-2.37**	-1.50
	(3.10)	(2.17)	(2.06)	(1.30)	(3.14)	(2.18)	(2.14)	(1.31)
	(0.00)	(0.04)	(0.05)	(0.21)	(0.00)	(0.04)	(0.04)	(0.20)
adj. R^2	0.73	0.73	0.73	0.73	0.77	0.75	0.77	0.75
DW	1.47	1.33	1.45	1.35	1.57	1.43	1.55	1.44
N. of obs.	33	33	33	33	33	33	33	33
ρ	0.90	0.92	0.90	0.91	0.88	0.91	0.87	0.90

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level

In the Tables 6.13 to 6.20 the complete estimation results of equation (6.3) for all pollutants are reported.

Table 6.13: Endogenous variable: first difference of SO_2

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	-2.40**	-2.87**	-2.19*	-2.62*	-2.39**	-2.85**	-2.19**	-2.61*
	(2.24)	(2.28)	(1.91)	(1.89)	(2.26)	(2.26)	(1.89)	(1.86)
	(0.03)	(0.03)	(0.07)	(0.07)	(0.03)	(0.03)	(0.07)	(0.08)
ΔY	8.6e-3	8.0e-3	8.1e-3	6.0e-3	2.3e-2	8.7e-3	2.3e-2	8.7e-3
	(1.36)	(1.19)	(1.24)	(0.86)	(0.67)	(0.25)	(0.65)	(0.24)
	(0.19)	(0.24)	(0.23)	(0.40)	(0.51)	(0.81)	(0.52)	(0.81)
ΔY^2	-2.7e-7	-2.4e-7	-2.5e-7	-1.8e-7	-1.2e-6	-2.6e-7	-1.2e-6	-3.3e-7
	(1.37)	(1.21)	(1.23)	(0.86)	(0.54)	(0.12)	(0.54)	(0.15)
	(0.18)	(0.24)	(0.23)	(0.40)	(0.59)	(0.91)	(0.59)	(0.88)
ΔY^3					1.7e-11	-1.7e-14	1.8e-11	2.9e-12
					(0.40)	(0.00)	(0.43)	(0.07)
					(0.69)	(1.00)	(0.67)	(0.95)
ΔS		-0.19		-0.06		-0.22		-0.07
		(0.33)		(0.10)		(0.37)		(0.11)
		(0.74)		(0.93)		(0.72)		(0.91)
ΔI			-26.43	-22.98			-26.58	-22.37
			(1.27)	(1.16)			(1.26)	(1.10)
			(0.22)	(0.26)			(0.22)	(0.28)
ECT^{b}	-0.27	-0.36**	-0.33*	-0.39**	-0.27	-0.36**	-0.34*	-0.38**
	(1.68)	(2.36)	(1.80)	(2.33)	(1.63)	(2.29)	(1.81)	(2.27)
	(0.10)	(0.03)	(0.08)	(0.03)	(0.12)	(0.03)	(0.08)	(0.03)
ΔD	28.74***	28.86***	26.70***	27.12***	28.83***	28.85***	26.78***	27.16***
	(12.81)	(13.39)	(9.90)	(10.46)	(12.53)	(13.03)	(9.76)	(10.21)
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
adj. R^2	0.86	0.87	0.86	0.87	0.85	0.87	0.86	0.86
DW	1.94	1.95	1.90	1.91	1.95	1.95	1.89	1.91
N. of obs.	32	32	32	32	32	32	32	32
ρ	0.51	0.56	0.54	0.60	0.49	0.54	0.54	0.59

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level
[b] ECT: particular error correction term, i.e. with or without Y^3, S and I.

Table 6.14: Endogenous variable: first difference of NO_x

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	-0.48	-1.02*	-0.93*	-1.26	-0.40	-0.40	0.12	-0.12
	(1.23)	(1.96)	(1.75)	(0.82)	(1.06)	(0.83)	(0.31)	(0.24)
	(0.23)	(0.06)	(0.09)	(0.42)	(0.30)	(0.41)	(0.76)	(0.81)
ΔY	5.9e-3*	6.1e-3*	2.2e-3	5.8e-3*	-2.5e-2	-6.1e-3	-3.6e-3	-6.6e-3
	(1.88)	(1.86)	(0.70)	(1.83)	(1.36)	(0.44)	(0.27)	(0.50)
	(0.07)	(0.07)	(0.49)	(0.08)	(0.19)	(0.66)	(0.79)	(0.62)
ΔY^2	-1.8e-7*	-1.7e-7*	-6.0e-8	-1.6e-7	1.7e-6	8.0e-7	6.0e-7	8.2e-7
	(1.97)	(1.80)	(0.64)	(1.66)	(1.57)	(0.94)	(0.73)	(0.99)
	(0.06)	(0.08)	(0.53)	(0.11)	(0.13)	(0.36)	(0.47)	(0.33)
ΔY^3					-3.7e-11*	-2.4e-11	-1.9e11	-2.4e-11
					(1.77)	(1.39)	(1.18)	(1.46)
					(0.09)	(0.18)	(0.25)	(0.16)
ΔS		-0.41		-0.33		-0.47*		-0.37
		(1.46)		(1.48)		(1.74)		(1.41)
		(0.16)		(0.15)		(0.10)		(0.71)
ΔI			-18.21**	-17.41**			-11.46	-15.30*
			(2.09)	(2.34)			(1.40)	(1.82)
			(0.05)	(0.03)			(0.18)	(0.08)
ECT^b	-0.18**	-0.26**	-0.23**	-0.72***	-0.32**	-0.71***	-0.78***	-0.79***
	(2.16)	(2.35)	(2.65)	(3.29)	(2.50)	(3.08)	(3.75)	(3.50)
	(0.04)	(0.03)	(0.01)	(0.00)	(0.02)	(0.01)	(0.00)	(0.00)
ΔD	-9.28***	-9.29***	-10.51***	-10.42***	-9.46***	-9.70***	-10.39***	-10.96***
	(8.45)	(8.97)	(8.61)	(10.58)	(8.80)	(9.88)	(8.85)	(9.41)
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
adj. R^2	0.77	0.77	0.78	0.85	0.77	0.80	0.81	0.82
DW	2.03	2.10	2.17	2.17	2.04	1.92	2.02	1.96
N. of obs.	32	32	32	32	32	32	32	32
ρ	0.19	0.42	0.49	0.88	0.21	0.32	0.37	0.36

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level
[b] *ECT*: particular error correction term, i.e. with or without Y^3, S and I.

Table 6.15: Endogenous variable: first difference of CO_2

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	-67.39	-101.6	-67.76	-101.9	-76.83	-108.2	-75.06	-110.1
	(1.04)	(1.46)	(1.04)	(1.37)	(1.32)	(1.48)	(1.20)	(1.40)
	(0.31)	(0.16)	(0.31)	(0.19)	(0.20)	(0.15)	(0.24)	(0.18)
ΔY	0.18	0.28	0.16	0.28	-2.17	-2.19	-2.04	-2.22
	(0.36)	(0.57)	(0.33)	(0.55)	(0.57)	(0.55)	(0.52)	(0.54)
	(0.72)	(0.57)	(0.75)	(0.59)	(0.58)	(0.59)	(0.61)	(0.59)
ΔY^2	-2.7e-6	-4.6e-6	-2.1e-6	-4.5e-6	1.3e-4	1.4e-4	1.2e-4	1.4e-4
	(0.18)	(0.32)	(0.14)	(0.31)	(0.59)	(0.60)	(0.54)	(0.59)
	(0.86)	(0.75)	(0.89)	(0.76)	(0.56)	(0.56)	(0.59)	(0.56)
ΔY^3					-2.5e-9	-2.6e-9	-2.3e-9	-2.7e-9
					(0.60)	(0.62)	(0.55)	(0.61)
					(0.55)	(0.54)	(0.59)	(0.55)
ΔS		-11.48		-11.85		-15.35		-16.35
		(0.36)		(0.35)		(0.45)		(0.45)
		(0.73)		(0.73)		(0.66)		(0.66)
ΔI			-337.8	-9.69			-346.8	58.14
			(0.30)	(0.01)			(0.30)	(0.05)
			(0.77)	(0.99)			(0.77)	(0.96)
ECT[b]	-0.46*	-0.63**	-0.51*	-0.62**	-0.52*	-0.60**	-0.55*	-0.60**
	(1.90)	(2.55)	(1.96)	(2.45)	(1.97)	(2.33)	(1.97)	(2.23)
	(0.07)	(0.02)	(0.06)	(0.02)	(0.06)	(0.03)	(0.06)	(0.04)
ΔD	-155.7	-113.5	-173.0	-115.2	-126.6	-115.9	-157.3	-112.9
	(1.20)	(0.89)	(1.12)	(0.75)	(0.94)	(0.88)	(0.99)	(0.72)
	(0.24)	(0.38)	(0.27)	(0.46)	(0.36)	(0.39)	(0.33)	(0.48)
adj. R^2	0.28	0.33	0.25	0.30	0.25	0.29	0.23	0.26
DW	1.47	1.46	1.46	1.46	1.52	1.51	1.50	1.50
N. of obs.	28	28	28	28	28	28	28	28
ρ	0.49	0.48	0.48	0.49	0.42	0.47	0.44	0.47

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level
[b] ECT: particular error correction term, i.e. with or without Y^3, S and I.

Table 6.16: Endogenous variable: first difference of PM

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	-0.10	-0.18	-0.13	-0.25	-0.15	-0.23	-0.16	-0.27
	(0.42)	(0.70)	(0.54)	(0.92)	(0.55)	(0.73)	(0.56)	(0.79)
	(0.68)	(0.49)	(0.59)	(0.37)	(0.58)	(0.47)	(0.58)	(0.44)
ΔY	3.7e-3*	3.6e-3*	3.7e-3*	3.8e-3*	-1.7e-2**	-1.6e-2*	-1.8e-2**	-1.8e-2**
	(1.98)	(1.91)	(1.94)	(1.98)	(2.19)	(2.05)	(2.37)	(2.42)
	(0.06)	(0.07)	(0.06)	(0.06)	(0.04)	(0.05)	(0.03)	(0.02)
ΔY^2	-1.1e-7*	-9.9e-8*	-1.1e-7*	-1.1e-7*	1.1e-6**	1.1e-6**	1.1e-6**	1.2e-11**
	(1.89)	(1.84)	(1.86)	(1.91)	(2.46)	(2.35)	(2.66)	(2.75)
	(0.07)	(0.08)	(0.07)	(0.07)	(0.02)	(0.03)	(0.01)	(0.01)
ΔY^3					-2.3e-11**	-2.2e-11**	-2.4e-11***	-2.5e-11***
					(2.73)	(2.61)	(2.90)	(3.00)
					(0.01)	(0.02)	(0.01)	(0.01)
ΔS		0.02		-0.02		-0.06		-0.10
		(0.12)		(0.14)		(0.43)		(0.73)
		(0.91)		(0.89)		(0.67)		(0.47)
ΔI			4.71	4.82			4.84	5.47
			(1.09)	(1.13)			(1.13)	(1.24)
			(0.29)	(0.27)			(0.27)	(0.23)
ECT[b]	-0.18***	-0.24***	-0.17***	-0.23***	-0.10***	-0.10***	-0.09***	-0.08***
	(4.80)	(4.92)	(4.71)	(4.88)	(2.87)	(2.87)	(2.84)	(2.82)
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)
ΔD	1.30**	1.33***	1.73**	1.74***	1.29**	1.25**	1.74**	1.75**
	(2.63)	(2.76)	(2.70)	(2.86)	(2.58)	(2.47)	(2.72)	(2.71)
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.01)	(0.01)
adj. R^2	0.57	0.56	0.56	0.55	0.60	0.58	0.60	0.58
DW	1.64	1.73	1.64	1.75	1.81	1.83	1.81	1.84
N. of obs.	32	32	32	32	32	32	32	32
ρ	0.23	0.29	0.24	0.29	0.21	0.22	0.21	0.21

t-statistics and marginal significance levels in parenthesis

*, **, *** for significance at the 10%, 5% and 1% level

[b] ECT: particular error correction term, i.e. with or without Y^3, S and I.

Table 6.17: Endogenous variable: first difference of CO

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	-6.34***	-5.31***	-5.78***	-5.43***	-7.94	-5.07***	-5.13***	-5.30***
	(3.63)	(3.02)	(3.34)	(2.93)	(0.05)	(2.92)	(2.95)	(2.89)
	(0.00)	(0.01)	(0.00)	(0.01)	(0.96)	(0.01)	(0.01)	(0.01)
ΔY	2.2e-2*	4.2e-3	1.4e-2	1.4e-3	1.3e-1**	1.9e-2	7.1e-2	2.1e-3
	(1.97)	(0.38)	(1.29)	(0.12)	(2.36)	(0.33)	(1.23)	(0.04)
	(0.06)	(0.71)	(0.21)	(0.91)	(0.03)	(0.75)	(0.23)	(0.97)
ΔY^2	-6.2e-7*	-1.6e-7	-4.2e-7	-7.3e-8	-7.0e-6*	-1.0e-6	-3.8e-6	-1.3e-7
	(1.80)	(0.51)	(1.29)	(0.23)	(2.01)	(0.30)	(1.08)	(0.04)
	(0.08)	(0.61)	(0.21)	(0.82)	(0.06)	(0.77)	(0.29)	(0.97)
ΔY^3					1.2e-10*	1.7e-11	6.5e-11	1.7e-12
					(1.73)	(0.26)	(0.94)	(0.02)
					(0.10)	(0.80)	(0.36)	(0.98)
ΔS		2.19**		2.19**		2.18**		2.12**
		(2.18)		(2.15)		(2.18)		(2.09)
		(0.04)		(0.04)		(0.04)		(0.05)
ΔI			-24.13	-10.37			-35.53	-9.43
			(0.68)	(0.32)			(1.02)	(0.29)
			(0.50)	(0.76)			(0.32)	(0.77)
ECT[b]	-0.16	-0.25***	-0.36***	-0.27***	1.7e-4	-0.33***	-0.47***	-0.36***
	(1.61)	(3.37)	(2.84)	(3.60)	(0.01)	(3.21)	(3.25)	(3.45)
	(0.12)	(0.00)	(0.01)	(0.00)	(0.99)	(0.00)	(0.00)	(0.00)
ΔD	4.70	4.90	2.92	4.00	3.67	5.29	2.13	4.41
	(1.11)	(1.33)	(0.60)	(0.86)	(0.77)	(1.17)	(0.45)	(0.97)
	(0.28)	(0.19)	(0.56)	(0.40)	(0.45)	(0.16)	(0.66)	(0.34)
adj. R^2	0.15	0.45	0.25	0.47	0.29	0.47	0.29	0.49
DW	2.18	2.05	2.08	2.06	2.02	2.04	2.05	2.04
N. of obs.	32	32	32	32	32	32	32	32
ρ	0.43	0.29	0.46	0.28	0.14	0.30	0.47	0.29

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level
[b] ECT: particular error correction term, i.e. with or without Y^3, S and I.

Table 6.18: Endogenous variable: first difference of NH_3

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	8.5e-6	0.06	0.01	0.07	0.02	0.12**	-0.01	0.09**
	(0.00)	(1.04)	(0.19)	(1.48)	(0.74)	(2.74)	(0.27)	(2.78)
	(1.00)	(0.31)	(0.85)	(0.16)	(0.47)	(0.01)	(0.79)	(0.01)
ΔY	8.0e-4	1.0e-3	2.2e-3***	2.0e-3***	1.6e-2***	2.2e-2***	9.7e-3*	1.8e-2***
	(1.34)	(1.30)	(4.79)	(4.16)	(3.95)	(5.53)	(1.77)	(6.93)
	(0.20)	(0.21)	(0.00)	(0.00)	(0.00)	(0.00)	(0.10)	(0.00)
ΔY^2	-2.7e-8	-3.5e-8	-6.5e-8	-6.1e-8***	-8.2e-7	-1.2e-6	-4.7e-7	-9.5e-7***
	(1.73)	(1.72)	(5.34)	(4.92)	(3.71)	(5.28)	(1.60)	(6.55)
	(0.10)	(0.10)	(0.00)	(0.00)	(0.00)	(0.00)	(0.13)	(0.00)
ΔY^3					1.3e-11***	1.9e-11***	7.1e-12	1.6e-11***
					(3.41)	(4.97)	(1.38)	(6.10)
					(0.00)	(0.00)	(0.19)	(0.00)
ΔS		0.03		0.05*		0.11**		0.12***
		(0.83)		(1.75)		(2.75)		(4.08)
		(0.42)		(0.10)		(0.01)		(0.00)
ΔI			3.65***	2.86***			2.49***	2.66***
			(3.52)	(3.22)			(3.01)	(4.22)
			(0.00)	(0.01)			(0.01)	(0.00)
ECT[b]	-0.19**	-0.85***	-0.77***	-0.95***	-0.44***	-0.41***	-1.22***	-0.58***
	(2.50)	(4.57)	(2.95)	(4.08)	(3.17)	(3.35)	(4.90)	(4.08)
	(0.02)	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)
ΔD	-0.46***	-0.26**	-0.02	-0.02	-0.45***	-0.30***	-0.05	0.01
	(3.80)	(2.59)	(0.16)	(0.19)	(4.18)	(2.90)	(0.43)	(0.07)
	(0.00)	(0.02)	(0.88)	(0.85)	(0.00)	(0.01)	(0.67)	(0.95)
adj. R^2	0.69	0.62	0.69	0.72	0.76	0.83	0.72	0.92
DW	2.03	2.28	1.95	1.77	2.04	1.98	1.87	2.08
N. of obs.	23	23	23	23	23	23	23	23
ρ	-0.34	0.55	-0.04	0.12	-0.36	-0.35	0.26	-0.40

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level
[b] *ECT*: particular error correction term, i.e. with or without Y^3, S and I.

Table 6.19: Endogenous variable: first difference of CH_4

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	-71.19	-1.76**	-70.94	-1.76**	38.61	-1.81***	-20.40	-1.80**
	(0.93)	(2.81)	(1.01)	(2.71)	(0.33)	(2.96)	(0.22)	(2.83)
	(0.37)	(0.01)	(0.33)	(0.02)	(0.75)	(0.01)	(0.83)	(0.01)
ΔY	7.0e-4	7.3e-4	1.7e-3	6.0e-4	-8.7e-2	-4.5e-2	-7.0e-2	-4.5e-2
	(0.08)	(0.11)	(0.20)	(0.09)	(1.06)	(0.73)	(0.73)	(0.71)
	(0.94)	(0.91)	(0.85)	(0.93)	(0.30)	(0.48)	(0.48)	(0.49)
ΔY^2	-1.9e-19	-1.4e-8	-3.3e-8	-1.1e-8	4.6e-6	5.4e-6	3.8e-6	5.4e-6
	(0.01)	(0.08)	(0.14)	(0.06)	(1.05)	(0.74)	(0.73)	(0.72)
	(0.99)	(0.94)	(0.89)	(0.95)	(0.31)	(0.47)	(0.48)	(0.48)
ΔY^3					-8.7e-11	-4.3e-11	-6.6e-11	-4.3e-11
					(1.04)	(0.76)	(0.72)	(0.73)
					(0.31)	(0.46)	(0.48)	(0.48)
ΔS		0.17		0.17		0.20		0.20
		(0.73)		(0.70)		(0.83)		(0.80)
		(0.48)		(0.50)		(0.42)		(0.43)
ΔI			8.68	-0.44			6.84	-0.80
			(0.84)	(0.06)			(0.68)	(0.10)
			(0.42)	(0.96)			(0.51)	(0.92)
ECT^b	0.05	-0.59***	0.04	-0.59***	-0.03	-0.58***	0.01	-0.58***
	(0.90)	(4.11)	(0.99)	(3.89)	(0.35)	(3.89)	(0.20)	(3.68)
	(0.38)	(0.00)	(0.34)	(0.00)	(0.74)	(0.00)	(0.85)	(0.00)
ΔD	-17.68***	-17.12***	-17.07***	-17.15***	-17.16***	-17.13***	-16.83***	-17.18***
	(16.34)	(22.51)	(12.35)	(18.23)	(16.57)	(21.64)	(12.75)	(17.49)
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
adj. R^2	0.94	0.97	0.94	0.97	0.95	0.97	0.94	0.97
DW	1.70	1.88	1.73	1.88	1.80	1.83	1.79	1.83
N. of obs.	23	23	23	23	23	23	23	23
ρ	0.52	0.68	0.46	0.68	0.72	0.65	0.63	0.65

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level
[b] *ECT*: particular error correction term, i.e. with or without Y^3, S and I.

Table 6.20: Endogenous variable: first difference of NMVOC

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
const	-0.83	-1.46**	-0.77	-1.34**	-0.71	-1.22*	-0.66	-1.11*
	(1.29)	(2.23)	(1.11)	(2.10)	(1.13)	(1.96)	(0.99)	(1.79)
	(0.21)	(0.04)	(0.28)	(0.05)	(0.27)	(0.06)	(0.33)	(0.09)
ΔY	-8.8e-5	-1.9e-3	9.5e-5	-1.8e-3	2.0e-3	2.9e-3	2.1e-3	2.8e-3
	(0.07)	(1.39)	(0.07)	(1.26)	(0.30)	(0.41)	(0.31)	(0.38)
	(0.95)	(0.18)	(0.95)	(0.22)	(0.77)	(0.69)	(0.76)	(0.71)
ΔY^2	-1.6e-8	3.5e-8	-2.1e-8	3.1e-8	-1.4e-7	-2.7e-7	-1.4e-7	-2.5e-7
	(0.38)	(0.84)	(0.49)	(0.72)	(0.34)	(0.60)	(0.34)	(0.56)
	(0.71)	(0.41)	(0.63)	(0.48)	(0.74)	(0.55)	(0.74)	(0.58)
ΔY^3					2.4-12	5.9e-12	2.3e-12	5.5e-12
					(0.29)	(0.67)	(0.27)	(0.61)
					(0.78)	(0.51)	(0.79)	(0.55)
ΔS		0.19*		0.20*		0.22**		0.23**
		(1.88)		(1.88)		(2.07)		(2.10)
		(0.07)		(0.07)		(0.05)		(0.05)
ΔI			-0.04	-0.24			-0.78	-1.00
			(0.01)	(0.07)			(0.23)	(0.28)
			(0.99)	(0.95)			(0.82)	(0.78)
ECT[b]	-0.50***	-0.45***	-0.51***	-0.46***	-0.52***	-0.46***	-0.54***	-0.48***
	(4.63)	(4.20)	(4.46)	(4.13)	(4.41)	(3.94)	(4.27)	(3.89)
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
ΔD	0.25	0.37	0.25	0.35	0.26	0.40	0.20	0.33
	(0.65)	(0.94)	(0.53)	(0.74)	(0.67)	(1.01)	(0.43)	(0.68)
	(0.52)	(0.36)	(0.60)	(0.47)	(0.51)	(0.32)	(0.67)	(0.50)
adj. R^2	0.43	0.40	0.41	0.38	0.42	0.40	0.40	0.38
DW	1.97	2.13	1.99	2.13	1.92	2.11	1.91	2.06
N. of obs.	32	32	32	32	32	32	32	32
ρ	0.87	0.86	0.88	0.86	0.87	0.86	0.88	0.86

t-statistics and marginal significance levels in parenthesis
*, **, *** for significance at the 10%, 5% and 1% level
[b] *ECT*: particular error correction term, i.e. with or without Y^3, S and I.

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Curriculum Vitae

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